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GETTING MANETS TO COMMUNICATE EFFICIENTLY: AN ANALYSIS OF MOBILE AD HOC NETWORK ROUTING SCHEMES IN TACTICAL COMMUNICATIONS

by

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June 2013

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There are many challenges to MANET implementation however, including management of the dynamic physical topology, and the efficient use of limited spectral and energy resources. One platform being tested by the Marine Corps utilizes a time-division multiple access (TDMA) scheme combined with Barrage Relaying to ensure robust communications. Other schemes for MANETs employ intelligent-routing protocols. This thesis examines those protocols and identifies the parameters needed to implement a tactical MANET routing scheme. The findings of this research advance understanding of MANETs and the elements necessary to enable their use in support of tactical communications; bringing the Marine Corps closer to its goal of lightweight and efficient tactical communications.

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GETTING MANETS TO COMMUNICATE EFFICIENTLY: AN ANALYSIS OF MOBILE AD HOC NETWORK ROUTING SCHEMES IN TACTICAL COMMUNICATIONS

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LIST OF ACRONYMS AND ABBREVIATIONS

AMPR	Aerial Mobile Ad Hoc Network Passive Relay
AODV	Ad Hoc On Demand Distance Vector
API	Application Programming Interface
ATH	At The Halt
BLT	Battalion Landing Team
C2	Command and Control
CBR	Case Based Reasoning
CENETIX	Center for Network Innovation and Experimentation
CLT	Company Landing Team
CMC	Commandant of the Marine Corps
COMSEC	Communications Security
DB	Decibel
DNA	Dynamic Network Architecture
DoD	Department of Defense
DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership, Personnel, and Facilities
DSDV	Destination Sequenced Distance Vector
DSR	Dynamic Source Routing
EFSS	Expeditionary Fire Support System
ECO	Enhanced Company Operations
EMO	Enhanced Marine Air Ground Task Force Operations
FSCC	Fire Support Coordination Center
GPS	Global Positioning System
HIMARS	High Mobility Artillery Rocket System
IP	Internet Protocol
JSON	JavaScript Object Notation
Kbps	Kilobits Per Second
LOE	Limited Objective Experiment
MAGTF	Marine Air Ground Task Force
MANET	Mobile Ad Hoc Network
Mbps	Megabits Per Second

MGRS	Military Grid Reference System
MHz	Megahertz
MIB	Management Information Base
MIO	Maritime Interdiction Operations
MMC	Mobile Ad Hoc Network Mission Configuration
MPH	Miles Per Hour
MPR	Multipoint Relay
NAT	Network Address Translation
NIC	Network Interface Card
NMS	Network Management System
NOC	Network Operations Center
NCW	Network Centric Warfare
OSI	Open Systems Interconnection
OSLR	Optimized Link State Routing
OTH	Over The Horizon
OTM	On The Move
PHY	Physical Layer
QoS	Quality of Service
RF	Radio Frequency
RREP	Route Reply
RREQ	Route Request
SACC	Supporting Arms Coordination Center
SNMP	Simple Network Management Protocol
SNR	Signal-to-Noise Ratio
TBRPF	Topology Based Reverse Path Forwarding
TC	Topological Control
TDMA	Time Division Multiple Access
TMN	Telecommunications Network Management Model
TTPs	Tactics, Techniques, and Procedures
TTV-C	Tactical Topology View-Controller
UTM	Universal Transverse Mercator
UWB	Ultra-Wideband
ZRP	Zone Routing Protocol

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I. INTRODUCTION

History often defines eras by its predominant technological advancement. The Bronze Age, the Iron Age, and the Industrial Age are just a few examples of eras associated with technology. Mobile devices are pervasive today, and computing devices are increasingly transitioning from the desktop system to smaller, lightweight and more portable laptops and tablet computers. Alberts, Garstka, and Stein (1999) observed that the dominant technology of the present day is information technology; therefore, this era is labeled the Information Age. The Marine Corps wants to use the tools of the Information Age to enhance warfighting capabilities in a revolutionary way. Mobile Ad-Hoc Networking (MANET) is an emerging technology whose potential presents an opportunity to greatly improve warfighting capabilities. The Marine Corps understands the need to maintain a competitive advantage in this age and the continuing requirement to adapt its Doctrine, Organization, Training, Materiel, Leadership Education, Personnel and Facilities (DOTMLPF) to defeat any adversary.

In previous ages, warfare adapted to dominant technologies (Van Creveld, 1985). The Information Age is no different, and Albert's et al. (1999) heralded this with their concept called Network Centric Warfare (NCW), where all elements of the warfighting apparatus are highly connected by electronic information networks down to the individual person or unattended sensor (Alberts, Garstka, & Stein, 1999). Network Centric Warfare is

> An information-superiority enabled concept of operations that generates increased combat power by networking sensors, decision makers, and shooters to achieve shared awareness, increased speed of command, higher tempo of operations, greater lethality, increased survivability, and a degree of self-synchronization. (Alberts et al., 1999)

The goal of NCW is to increase combat effectiveness through the increased awareness and knowledge throughout an organization, enabling through faster decision cycles (Alberts, Garstka, & Stein, 1999). In essence, the network and its infrastructure becomes a key enabler that promotes increased tempo and self-synchronization of operations.

The acquisition of information and knowledge is very important, but collecting information must neither decrease the tempo of operations nor foster indecisiveness. The fundamental nature of warfare is a forceful struggle between opposing entities, and the "enemy always gets a vote." Decisiveness is paramount to Marine Corps' Command and Control (C2) processes and execution because it puts the enemy in a reactionary mode, where the enemy's actions/reactions are dictated by the Marine Leader. Mission Command maximizes combat effectiveness by ensuring decisive action despite uncertainty and time constraints (United States Marine Corps, 1996).

Mission Command is predicated on a commander assigning missions to subordinates and communicating his or her intent. Commander's Intent articulates the commander's vision of success on the battlefield; it represents the desired end-state. The commander executes mission tactics by assigning a mission (or task) to subordinates with constraints, but does not define how the subordinate is to execute the mission. This in turn fosters the creativity of the subordinate in the planning and execution of the assigned mission. Furthermore, should the overall situation change, the subordinate is allowed to adapt plans and operations as long as they are in line with the commander's intent.

Mission Command will always be the backbone of Marine Corps leadership in warfare, but tactics, techniques and procedures (TTPs) that the warfighter use constantly adapt to the enemy and the environment. While he was the Commandant of the Marine Corps, General Conway set the path for how the Marine Corps would conduct warfare in the 21st Century in Marine Corps Vision and Strategy 2025 (2008). Although it preceded the Marine Corps strategy document, FORCEnet (Clark & Hagee, 2005) is the functional concept that supports that future vision and strategy. FORCEnet applies the concept of NCW in the Information Age to the Marine Corps C2 doctrine. The objective of FORCEnet is not to eliminate uncertainty; instead FORCEnet seeks to enhance the commander's decision-making process and the effective execution of his intent across the force (Clark & Hagee, 2005). FORCEnet describes the concept of a ubiquitous network that increases the quality, quantity and timeliness of information products and services available to the warfighter.

The goal of FORCEnet is to connect the greatest number of sensors, units, weapons, commanders and staffs as possible because when such a state exists, all the benefits of decentralization (e.g., initiative, adaptability, and increased tempo) can be realized while simultaneously realizing the benefits associated with a centralized C2 architecture—i.e., coordination and unity of effort (Clark & Hagee, 2005). Admiral Clark and General Hagee established a 2015-2020 deadline for FORCEnet, and they delineated the core capabilities needed to achieve it. The core capabilities, when realized, shall enable a robust, reliable, and interoperable C2 structure that (1) conveys accurate friendly and known enemy position location information, (2) automates minor decisions, and (3) efficiently presents relevant information to the commander.

MANET is one technology that is capable of contributing to the accomplishment of those goals. Mobile Ad Hoc Networking is beneficial in many applications where an underlying communications infrastructure is not present, or the establishment of one is not advantageous (Basagni, Conti, Giordano, & Stojmenovic, 2004). MANETs are rapidly deployable, scalable, and capable of connecting nodes that are beyond line of sight (Basagni, Conti, Giordano, & Stojmenovic, 2004). MANETs also extend existing infrastructure-based networks (e.g. Wide Area Networks) to the tactical edge, which manifests the vision of the network effect.

There are many challenges in the design and implementation of MANETs. One of the unique challenges to MANETs is network management. Due to the dynamic physical topology and decentralized architecture, fault detection and performance monitoring is difficult (Basagni, Conti, Giordano, & Stojmenovic, 2004). In addition, MANETs are constrained by bandwidth and energy limitations due to their high mobility. (Basagni, Conti, Giordano, & Stojmenovic, 2004). To mitigate these challenges, a resource efficient autonomous network management system must be employed. A potential solution would involve the hypernode concept (Bordetsky & Hayes-Roth, 2007). Hypernodes operating above the application layer (the eighth Layer) could use *case based reasoning* to make network management decisions based on environmental factors. Multiple MANET transmission and routing schemes have been developed, and researchers continue to tackle the many challenges associated with MANET routing.

There are two main categories of information routing techniques used in current MANET systems: the *barrage relay scheme*, and the *intelligent routing scheme*. The *barrage relay scheme* employs every node other than the source and destination node as a relay. The *intelligent routing scheme* determines the best path between the source and destination before sending a message. The problem identified and analyzed by this thesis is the determination of an effective routing metric for use in intelligent routing---a key component of MANET operation. In examining this problem, the following research questions emerge: (1) What are the relevant factors in establishing the cost of each link for a given route between a source and destination, (2) Can those factors be measured, (3) How can a case-based reasoning (CBR) approach be applied to maximize the effectiveness of an intelligently routed MANET (4) What are some key factors needed in a CBR case, and (5) Can that information be captured using the system's current network management platform?

The platform used in conducting this research is the TrellisWare CheetahNet II TW-230 radio system. The CheetahNet II TW-230 is a man-portable MANET platform that operates under low power. The CheetahNet radio systems are currently being evaluated by the Marine Corps Warfighting Lab for their ability to extend infrastructure based networks to units on the move (OTM) and at the halt (ATH).

A potential benefit to this study is that it could advance the Marine Corps towards its goal of robust, reliable tactical communications as envisioned in FORCEnet. This thesis identifies key variables necessary for a useful case and the optimal means to collect the values of those variables. Recommendations on intelligent routing approaches for MANETs are also addressed.

The thesis is organized into the following chapters. Chapter II presents the background principles associated with Mobile Ad Hoc Networks, and it provides a summary of recent research on MANETs. Chapter III dictates the method of conducting research for the thesis, and it outlines relevant metrics to be captured during field experiments. Chapter IV presents and analyzes the data collected during the experiments. Chapter V summarizes the thesis, presents the conclusions, and makes recommendations for future research.

II. BACKGROUND AND LITERATURE REVIEW

This chapter represents a summary of the literature that led to the determination of gaps in the ability of MANETs to support the information exchange capabilities of tactical team at the edge of the battlespace to achieve the capabilities envisioned in the Marine Corps Vision and Strategy 2025 (2008). In addition, the background and literature review from whence this chapter came also aided in the design of the experiments used to answer the research questions posed in Chapter 1.

A. BACKGROUND

1. Routing

Routing is the process of directing data in a network (Dean, 2013). Routing is conducted either statically or dynamically. In static routing, an administrator directs the path of information from a source to a destination in or among networks (Dean, 2013). In dynamic routing, a connectivity device determines the best route between a source and destination. Dynamic routing generally occurs at Layer 3 of the OSI model (Dean, 2013).

Routers are connectivity devices that perform routing (Dean, 2013). Although routers can be configured to process static routes, it is not the optimal configuration due to the continuously changing state of networks (Dean, 2013). There are three types of routers: interior, exterior, and gateway routers (Dean, 2013). Interior routers direct traffic among nodes in a network; exterior routers direct data between networks; and gateway routers connect interior routers to exterior routers (Dean, 2013). Routers rely on routing tables, which store routes for destinations and destination networks.

Routers direct data based on routing protocols. Routing protocols determine the best path to a destination. The best path is considered the most efficient path between the source and destination (Dean, 2013). Routing protocols determine the best path based on a routing metric (Dean, 2013), which is a way assigning a value to a specific path. Routing metrics are assigned to a path based on many factors, including the number of hops between to the destination, the throughput of a path, the delay along a path, and the

reliability of a path (Dean, 2013). There are three categories of routing protocols: Distance Vector, Link State Routing, and hybrid protocols (Dean, 2013). Hybrid protocols employ a combination of Distance Vector and Link State Routing protocols; therefore they will not be discussed in further detail.

Distance Vector protocols determine the best route based on the distance to a destination, although some protocols take into account the number of hops to a destination or the delay to a destination. Routers that employ Distance Vector routing share information in their routing tables to their neighboring routers; each router relies on routes given by its neighbors in constructing and updating a routing table for destinations beyond one hop away (Comer, 2009).

Link State Routing protocols differ from Distance Vector protocols in two major ways. Routers that employ Link State Routing broadcast link-state information to all the nodes in the network, as opposed to specific routing table information transmitted by routers employing the Distance Vector protocol. The broadcasting of the state of each individual link allows each node to create a network topology that shows how all the nodes are connected. In addition, each node can use this information to independently determine the best path for a packet travelling to a specific destination node (Dean, 2013). This is different from distance vector protocols, where each node relies on routing table information from its neighboring nodes in determining the best path to a destination.

2. Mobile Ad Hoc Networks

MANETs are uniquely identified by five characteristics: wireless, ad-hoc based, autonomous and infrastructure-less, multi-hop routing, and mobility (Basagni, Conti, Giordano, & Stojmenovic, 2004). The first characteristic is self-explanatory, and therefore will not be explained in further detail. An ad-hoc based network is temporarily formed as needed, and dynamically reacts to changes into the network topology in order to maintain a complete network. MANETS are autonomous and infrastructure-less in that they do not depend on any central management node for connectivity and communication across the network; each node communicates directly with other nodes in peer-to-peer fashion. In multi-hop routing, each individual node is a router, forwarding

the packets it receives. The individual nodes are mobile, and the topology of the nodes is constantly changing due to node mobility.

There are many challenges associated with managing and implementing MANETs. Due to the lack of infrastructure and a central management entity, fault detection and management, is difficult. The dynamic nature of the network topology can lead to network splits and packet loss. An example of a situation where a network split occurs is shown in Figure 1.

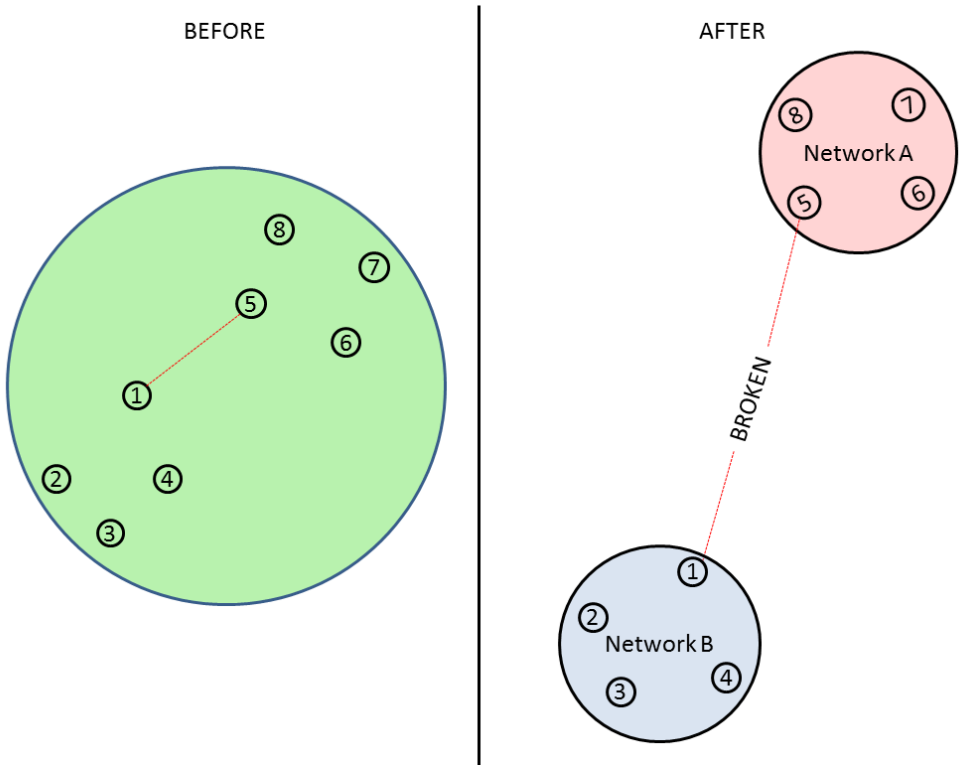

Figure 1. The network splits due to the severing of the link nodes 1 and 5

MANETs, being wireless networks, are also susceptible to challenges that traditional wireless networks deal with, such as higher rates of packet loss and collisions. Another challenge MANETs share with traditional wireless networks is the limited bandwidth and the resultant lower data transmission capacity. The benefit of mobility in MANETs is offset by the (relative) lack of reliable power sources when compared to traditional wired networks. In addition to situations where packet loss occurs due to

broken connections in the network, packet loss may also occur due to because overloaded nodes. Overloaded nodes may drop packets when its received packets queue is full; if the network management system does not manage this situation, sending or receiving nodes will have no knowledge of the packet loss. The broadcasting of information always presents a security challenge in wireless networks, and MANETs are no different in this respect. Lastly, it is difficult to provide quality of service (QoS) guarantees when the topology and reliability of the network nodes are dynamic.

3. Ad Hoc Routing Protocols

Belding-Royer (2004) explains that most, if not all, routing protocols for MANETs have common assumptions and design goals. MANET routing protocols operate under the following assumptions: all nodes have equal resources and capabilities (e.g., range), bidirectional communications occur, networks consist of approximately 10–100 nodes, and battery power is the greatest operating constraint. MANET routing protocols therefore generally have the following design goals: (1) minimization of necessary control and processing overhead to maximize bandwith and power resources available to the user for information transmission, (2) use of multihop routing techniques to transmit messages from the source to destination node when the two are outside the source's maximum transmission range, (3) management of the dynamic topology of the networks in order to maintain a constant source-destination path for every node pair in the network, and (4) the prevention of message loops which tie up necessary bandwidth. The different protocols can be categorized as either proactive, reactive, or hybrids.

a. Proactive Protocols

Proactive protocols are derived from traditional distance vector and link state protocols, where each node always maintains an up to date route to every other node in the network. Route creation and maintenance occurs periodically or after an event is triggered (e.g., when a link is added or removed). A key difference in proactive protocols as opposed to traditional routing protocols is the rate of updates. Updates occur at different rates based on the speed of nodes. The advantage of proactive protocols is that a route is immediately available when needed. The instant route availability comes with

a significant control overhead cost in large networks or rapidly moving nodes. Destination Sequenced Distance Vector routing (DSDV) and Optimized Link State Routing (OSLR) are two proactive protocols studied extensively in MANET research (Belding-Royer, 2004).

DSDV is a distance vector routing protocol that uses sequence numbers to maintain the most up to date routes. Like all distance vector protocols, DSDV nodes are only aware of their nearest neighbors; each node must rely on routing information from its nearest neighbors. Each node has a routing table that contains the destination (Internet protocol) IP, destination sequence number, next hop IP address, hop count, and the install time. The sequence number identifies the most recent determined route to a destination in the case that multiple routes exist; a higher sequence number represents a newer route. The install time is used to identify when the route will expire (stale) (Perkins & Bhagwat, 1994). Routing table update messages are sent to other nodes, containing the destination IP, destination sequence number, and hop count. There are two types of routing table updates: full and incremental (Perkins & Bhagwat, 1994). Full updates send a node's full routing table, and incremental updates send only those routes that have changed since the last update. Full updates are sent sparingly; incremental updates are sent more frequently because there is less overhead associated with them. If a node receives two next hop paths to a destination, the node chooses the path with the largest destination sequence number (an indicator of the most updated route). If two paths have the same destination sequence number, then the node chooses path with lowest hop count.

Optimized link state routing improves on traditional link state routing by adding multipoint relays (MPRs) to reduce network overhead (Belding-Royer, 2004). Each node chooses its own MPR according to which nodes will retransmit a message to each of the original node's two hop neighbors. Only the MPRs rebroadcast the original node's messages. Figure 2 shows a network of nodes with the multipoint relays shaded.

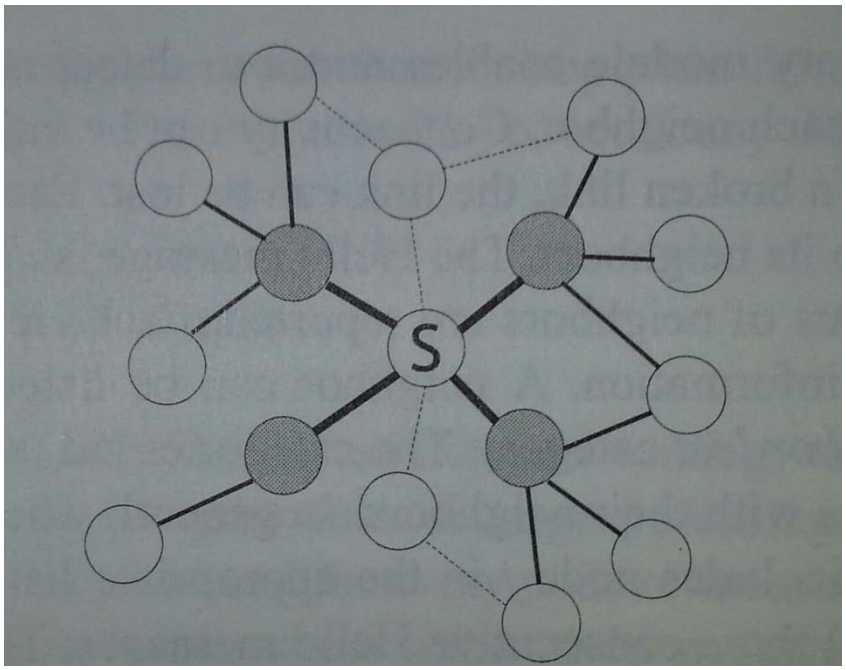

Figure 2. Multipoint Relays (From Belding-Royer, 2004).

Nodes determine their two hop neighbors from “hello” messages. Each node transmits a “hello” message that contains a list of its neighbors. When a node receives this message, it can ascertain its two hop neighbors simply by observing the neighbors of its immediate neighbor. In addition to “hello” messages, topological control (TC) messages are sent periodically that contain the list of nodes that have selected a given node as an MPR. .

The Topology Based Reverse Path Forwarding (TBRPF) protocol is another link state routing based protocol (Belding-Royer, 2004). Each node computes a shortest path tree to all other nodes, but it only transmits a subset of the tree. There are two modules: a neighbor discovery module and a topology module. The neighbor discovery module detects neighbors and determines the status of each neighbor. The possible neighbor statuses are: neighbor request, neighbor reply, and neighbor lost; a node will categorize each of its neighbors according to these three categories. Nodes periodically send “hello” messages to update their status. The *neighbor request* list is a list of nodes from whence the current node has received an initial Hello message. The *neighbor reply* list is a list of nodes from which the current node has received a “hello”

message from after it has sent out a "hello" message to those nodes. The *neighbor lost* list contains a list of nodes from which a node has not received a reply hello message from. Routing occurs by computing the shortest path source tree using a variant of Dijkstra's algorithm (Belding-Royer, 2004). Only the Reportable Subtree (RT) is transmitted.

b. Reactive Protocols

Reactive Routing Protocols differ from proactive protocols: each node discovers routes only when needed; if a route does not already exist in the routing table or the current route has expired, the source node will initiate the route discovery process. The advantage of reactive routing protocols is that signaling overhead is lower than that of proactive protocols, especially in moderate traffic conditions (Belding-Royer, 2004). The disadvantage is the increased delay associated with route determination when sending a message. The Ad-Hoc On Demand Distance Vector (AODV) protocol and the Dynamic Source Routing (DSR) protocol are examples of reactive protocols.

Like the proactive routing protocols, AODV uses sequence numbers to ensure the most recent path is chosen for routing to a destination. When a source node needs to send a packet to a destination, it first checks its routing table to see if it has an expired route. If the route exists, then the packet is forwarded using the route from the table; if no route or an expired route exists, then the source node initiates the route discovery process by issuing a Route Request (RREQ) packet, which contains the source address, the destination address, the last known sequence number of the destination, the hop count, and a new sequence number assigned to the route request (Belding-Royer, 2004). An intermediate node receives the RREQ and checks to see if it has a route to the destination in its routing table. If it does, then it compares the destination sequence number it has to the destination sequence number included in the RREQ packet for staleness. A stale route is one that has a lower destination sequence number than the one included in the route request packet. If the intermediate node has a stale route, then it increments the hop count and forwards the request on. If it has the most recent hop count, then it sends a route reply (RREP) message back to the sender with the known

route to the destination. If the source receives more than one RREP, it chooses the route with the greatest sequence number, then the smallest hop count. In the case that a link goes down, each node will send a route error (RERR) packet to all nodes in its routing table that used that link to get to a particular destination. Each node forwards the packet upstream to any other nodes that used the link.

Dynamic Source Routing is similar to AODV with a couple of notable differences. DSR is a source routing protocol where data packets contain the full route to the destination and the next hop is not determined at each intermediate hop (Belding-Royer, 2004). During the route request process, each intermediate node that does not have a route to the destination appends its own address to the original RREQ and then forwards the message. When a node that does have a route to the destination receives the route request packet, it appends the known route from its routing cache to the route travelled by the route request packet, creating a full route from source to destination (Belding-Royer, 2004). The intermediate node sends this full route back to the source in a RREP message. DSR has a route cache instead of a route table, which contains multiple routes to the destination. DSR nodes can exercise promiscuous listening. Promiscuous listening occurs when a node receives a packet not addressed to it, retaining the routing information stored in the packet for its own routing cache (Belding-Royer, 2004). An example of the DSR RREQ / RREP process is demonstrated in Figure 3 (Belding-Royer, 2004). In the example, the source node, marked “S”, sends a route request, attempting to find a viable route to the destination, marked “D”. The RREQ message arrives at the destination because none of the intermediate nodes has a viable route in their caches. The destination node upon receiving the request sends the routing information already in the RREQ message back to the source in a RREP message.

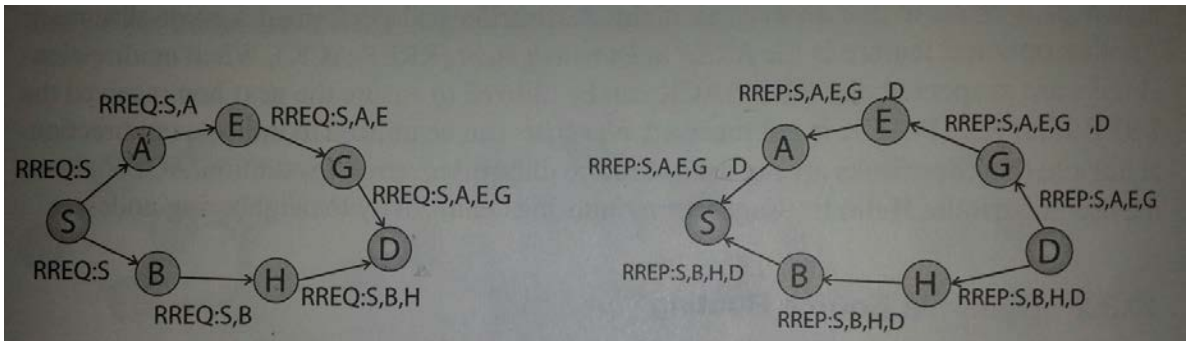

Figure 3. DSR Route Request and Route Response (From Belding-Royer, 2004).

c. Hybrid Protocols

Hybrid Protocols exhibit a combination of proactive and reactive protocol characteristics based on specific circumstances. An example of a hybrid protocol is the Zone Routing Protocol (ZRP). In the Zone Routing Protocol, a zone is established based on a predetermined number of hops extending out from each node. A ZRP node executes a proactive routing protocol within its zone. Routes to all destinations within the zone are continuously known and updated. A ZRP node uses the Intrazone Routing protocol for maintaining routes within the specified zone. The Intrazone Routing protocol is a link state routing protocol. ZRP uses an Interzone Routing protocol for destination nodes that are outside of the predefined zone. The Interzone Routing Protocol is reactive protocol that establishes routes only when necessary. When a source node wishes to send a message to a node that is outside its zone, the route discovery process begins. To execute the Interzone Routing Protocol, ZRP uses peripheral nodes. For a given node, the peripheral nodes are those nodes that are at the maximum number of hops away from the sending node equal to the zone radius. Figure 4 shows the zones for node “S” with a zone size of two hops, and peripheral nodes (i.e., A, B, C, and D).

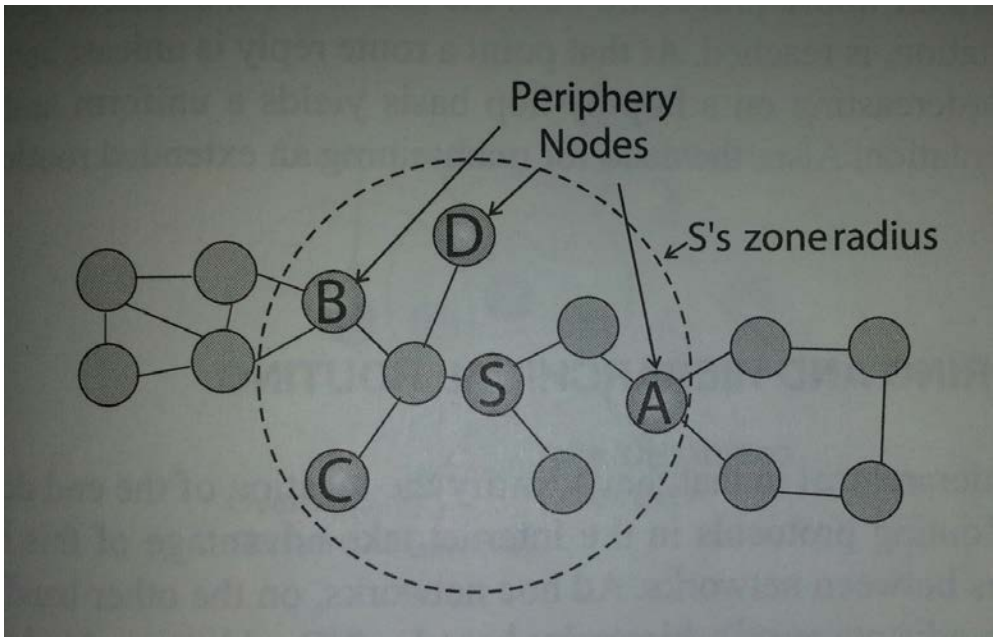

Figure 4. ZRP 2-Hop Zone with Periphery Nodes Shown (From Belding-Royer, 2004)

For a destination that is not within the predefined zone, the original node *bordercasts* the route requests to the peripheral nodes (Belding-Royer, 2004). Bordercasting is sending a message to a node's periphery nodes requesting a route to a destination. In Figure 4 above, node "S" would bordercast route request messages to nodes "A", "B", "C", and "D" if it wished to send a message to a node that is not in its two-hop zone, identified by the broken-line circle. If the destination is within the zone of one of the peripheral nodes, then that particular peripheral node sends back the route to the original source; otherwise the peripheral nodes bordercast the message to their peripheral nodes. This process continues until a route to the destination is identified.

4. Decision Support Systems

Decision support systems serve two purposes; they solve anticipated and occurring problems, and they present problems they cannot solve through an interface that is suitable for human understanding. Lewis (1995) presents two categories of decision support systems used in managing computer networks: (1) Expert Systems, also known as rule based reasoning systems, and (2) case based reasoning systems.

Rule based reasoning breaks problems into “if...then” statements. There are three basic components to expert systems: the working memory, the rule base, and the inference engine. The working memory is a repository of dynamically changing facts about the environment (Lewis, 1995). The rule base is the repository of “if-then” rules that are used for problem solving. The inference engine compares the facts in the working memory to the rule based to determine which actions need to be taken. The Rule based Reasoning components with their interactions are depicted in Figure 5.

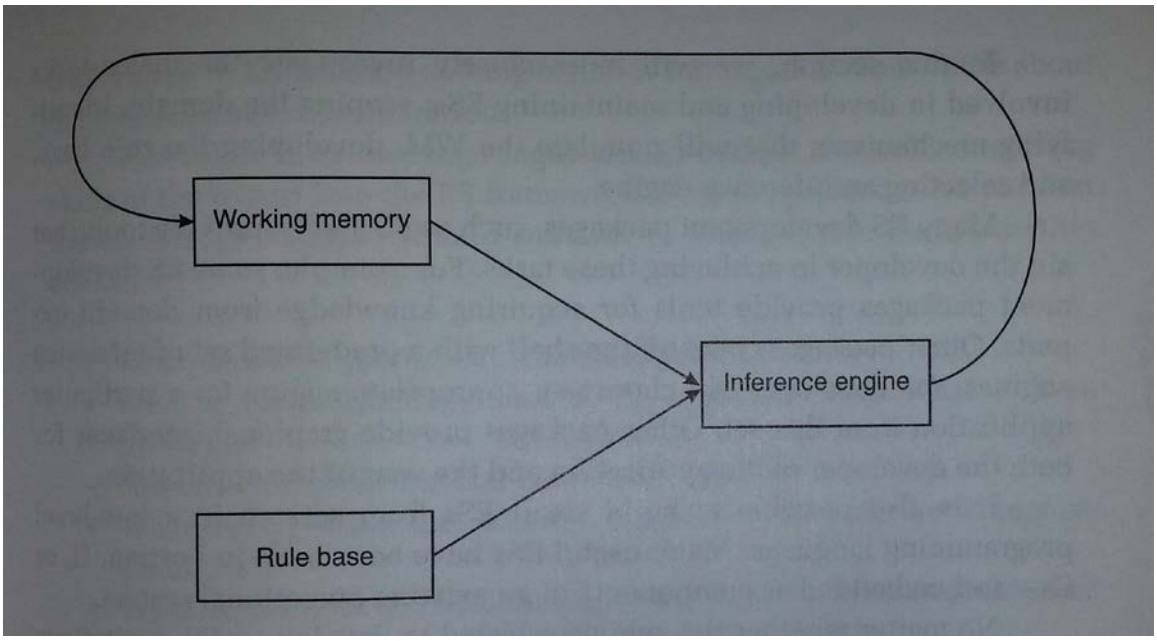

Figure 5. Rule Based Reasoning Model components and interactions (From Lewis, 1999).

Case based reasoning is another knowledge management and problem solving method that uses cases for problem solving. Case based reasoning consists of four modules: case retrieval, case adaptation, case execution, and case organization (Lewis, 1995). Lewis (1995) likens a case to an empty questionnaire form. There are generally three types of information in a case: a primary question or problem, supporting or background information, and information on the proposed or actual solution and whether it was successful. Case retrieval is where a network problem case is matched with a similar case in the case library. Case adaptation is the adaptation of the solution of the

case from the case library to the new problem case. Case execution is the implementation of the solution and the evaluation of the success of the case. Case organization is how the new case is stored in the case library after case execution. This thesis focuses on the case library for network management systems, and explores the details of cases that occur in decentralized networks. The key variables under consideration include the network status of nodes and the environment. The CBR model with component interactions is depicted in Figure 6.

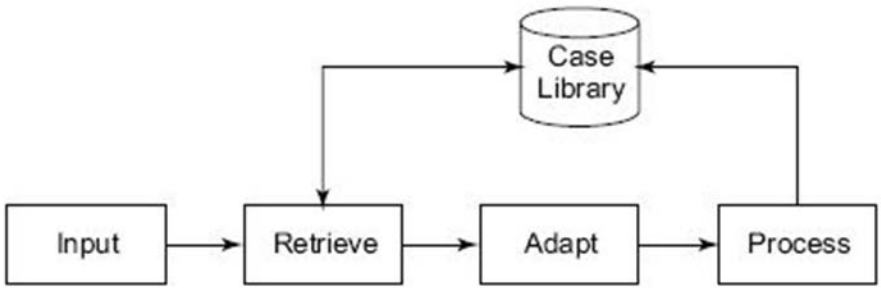

Figure 6. CBR Model components and interactions (From Subramanian, 2010)

Lewis criticizes expert systems for their brittleness; if the inference engine encounters a situation for which there is no rule, then the system is unable to process the problem. Case based reasoning excels in this arena because of its case adaptation feature; a CBR system will make attempts to modify a previous solution to a new one, if the cases do not match completely.

B. LITERATURE REVIEW

1. Kioumourtzis: Simulation and Evaluation of Routing Protocols for Mobile Ad Hoc Networks

Kioumourtzis (2005) identifies and outlines the key MANET proactive, reactive, and hybrid routing protocols circulating in the research community. Kourmourtzis also identifies the protocols most suitable for DOD implementation based on assessment of their operating characteristics from a tactical perspective, and he performs a quantitative

analysis of those selected protocols using simulation software. Qualitative metrics used in evaluation included loop-free behavior, unidirectional link support, and multicasting ability. Based on the advantages and disadvantages of each protocol, he determines that of the current MANET routing protocols, the Ad-Hoc On Demand Distance Vector (AODV), the Dynamic Source Routing (DSR), and the Optimized Link State Routing (OSLR) protocols were most suitable to the DoD, and those protocols were tested in his computer simulation. Quantitative metrics recorded in the simulation included packet delivery ratio, average end-to-end-delay, normalized routing load, and normalized MAC load. Kioumourtzis concluded that there is no one best routing solution that performs best in all tactical scenarios. Therefore, it is incumbent on network managers to understand each protocol's tradeoffs over the spectrum of situations. OLSR is optimal in situations of low network congestion for delivering voice and video transmissions; AODV is more suitable in networks with high mobility and connectivity that consist of 90 or more nodes; and DSR performs best in situations with high connectivity, a small number of nodes (up to 100) and low mobility (Kiourmourtzis, 2005).

2. Bordetsky and Hayes-Roth: Extending the OSI Model for Wireless Battlefield Networks: a Design Approach to The 8th Layer For Tactical Hypernodes

Bordetsky and Hayes-Roth (2007) propose a network management scheme to implement Command and Control in a network centric environment. Bordetsky in his past experiments demonstrated an autonomous capability to link multiple human-ran Network Operating Centers (NOCs) over large distances (up to 100 miles apart) using unmanned aerial vehicles to plug gaps in coverage. The Network Operation Center functions become extremely difficult when individual nodes are moving at rapid rates of speed; such conditions create rapidly changing network situations that cannot be adequately managed by humans due to delays in information travel time between nodes and processing time within nodes. As a result, the authors propose the addition of an

eighth layer[1] with "hypernodes" that individually act as NOCs. The hypernodes would be able to perform three major functions associated with the telecommunications management network model: Network Element Management and Network Management, Service Management, and Business Management. The Simple Network Management Protocol is already used to implement Network Element and Network Management. Its network management capability could be theoretically extended to include a fault management capability, which utilizes resident memory in the form of cases based on Lundy Lewis' Case-Based Reasoning approach.

3. Gateau: Extending Simple Network Management Protocol Beyond Network Management: A MIB Architecture for Network-Centric Services

Gateau (2007) describes the utility, simplicity, universality, security, and extendibility of SNMP for network management. Gateau expands Albert's (1999) three domains of information flow, adding two domains (i.e., the technological and decision support domains) that act as interfaces between the physical, information, and cognitive domains. The technological domain nests itself between the physical and information domains, and comprises those specific technologies that process, store, and manage data and information. The decision support domain resides between the informational and cognitive domains and shapes information into a useful form for processing in the cognitive domain.

Gateau sees utility in Bordetsky and Hayes-Roth's eighth layer concept and the use of hypernodes performing two Telecommunications Management Network (TMN) model functions. Service-management level aware hypernodes can be queried via SNMP about network services available and the status of the aforementioned services, and network element level (sub-network) aware hypernodes can maintain the status (up or down) of all nodes attached to their sub-network. Gateau also describes a decision support function where hypernodes can either send decisions or be queried on decisions

[1] The OSI Model is an abstract representation that describes how network communications occur (Dean, 2013). It contains seven layers: physical, data link, network, transport, session, presentation, and application layers. Bordetsky and Hayes Roth propose an additional layer that exists above the application layer. For more information on the OSI Model and its individual layers, see Dean (2013).

made by humans regarding the network. Gateau analyzes a Maritime Interdiction Operations (MIO) experiment from a network management perspective, categorizing the types of messages sent in the management process. He observed nine categories of messages: requests for service, requests for information, responses/amplifications, unsolicited information, network registration/deregistration, service/status announcements, decision requests, decision announcements/ task assignments, and situation reports. Gateau creates an architecture for three types of hypernodes that would handle these types of messages: a service aware hypernode, a subnetwork aware hypernode, and a decision support aware hypernode. His design includes a MIB for each type of node.

4. Gruber: Integration and Management of Emerging Tactical Mesh Networks Combined with Unattended Sensor Networks, Ultra-Wideband Links, and Ad-Hoc Mobile Tactical Radios.

Gruber (2011) evaluates the effects on ultra-wideband propagation in shipboard and urban environments, and assesses the capabilities of sensor and radio MANETS to provide reliable transmission of sensor information to tactical operations centers. Based on the above context, he evaluated two systems: the Trident Systems Ultra-Wideband (UWB) Recce Node Unattended Ground Sensors and the TrellisWare CheetahNet TW-220 radio systems. The Trident System was tested in both environments, while the CheetahNet radio was tested in a shipboard environment. The Trident system did not show a significant penetration capability (i.e., the ability of a signal to pass through solid objects, such as walls) in either environment but produced throughputs in the 16 Mbps range. The CheetahNet radios, under LOS conditions in the shipboard environment, produced throughput in the 68–97 Kbps range. Gruber's assessment was that the data rate of the CheetahNet 220s was insufficient to provide a reliable reach back capability (i.e., the ability to transmit video and other forms of data that require higher data rates and do not react well to high jitter rates). Gruber also provides an overview of both systems Network Management Capabilities, and recommends a new network management capability that consists of a SNMP manager-agent network architecture. The SNMP architecture would use a case-based reasoning system to automate network

management functions, with case information being available through local MIBs. Gruber also recommends potential case information, including Position Location Information, link health, network health, and bandwidth availability. Given these elements, MANET nodes could position themselves to optimize the operation of the network without human intervention.

5. Puff: Network Management System for Tactical Mobile Ad-Hoc Network Segments

Puff (2011) assesses the value of Tactical Mobile Ad-hoc Networks to the Marine Corps' Enhanced Marine Air Ground Task Force (MAGTF) Operations / Enhanced Company Operations concepts. Puff also establishes a theory of how a Network Management System (NMS) could be used to obtain even more value out of MANETs. Puff theorizes that Bordetsky & Hayes Roth's (2007) hypernode operating at the eighth layer could perform decentralized network management for MANETs. Hypernodes would request information from other network nodes and change the values of certain properties of those nodes by altering one or more variables in a node's SNMP Management Information Base (MIB). Since SNMP is an extensible protocol[2], additional network management specific variables can be included in a network agent's MIB. Puff identifies fifteen such variables that a hypernode would use to monitor, and when necessary, improve network performance.

6. Rivera: Distributed Agent Based Networks in Support of Advanced Marine Corps Command and Control Concept

Rivera (2012) suggests that the tactical nature of combat and its communications support infrastructure have a symbiotic relationship where operational success depends on the network, and the network depends on the operation's execution. Rivera puts forth a hybrid network management model that combines both hierarchical and decentralized architectures, using network management nodes that employ contextual analysis and case-based reasoning to solve network problems. This hybrid system is called an

[2] SNMP is extensible in that new functionality can be added to the protocol through the creation of new variables to represent properties of a managed system.

autonomic system, where policy-based network management functions establish overall objectives, and contextual information is used by the system to adapt the network structure in accordance with established policies. Rivera hypothesizes that the Signal-to-Noise Ratio (SNR) hop count, and power output are good indicators of network quality and availability, and therefore are an important tool in the predictive network management of MANETs.

Rivera observed the SNRs of TrellisWare CheetahNet TW-220 radios in the field using the HEAT Map interface created by research in NPS' CENETIX lab. Rivera concludes that to evolve from managed networks to autonomic networks, a mechanism that enables predictive and adaptive capabilities is required; however, Rivera does not create an example of such a mechanism. Rivera posits that these capabilities (policy creation, policy execution, and contextual awareness) must exist in every node in the network.

The background and literature review provided a foundation for understanding networks and network management systems. The research that led to the background section helped me to grasp the concept and operation of MANETs. In addition, the literature review helped me to identify gaps in research which led to the formulation of the problem analyzed in this thesis. The conduct of the literature review also gave me a basic understanding of the TrellisWare CheetahNet family of radios, but in order to really experiment with them, a much deeper understanding of the radio systems and underlying technology was required.

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III. RESEARCH METHODOLOGY

The concept examined by this thesis is that each node in the MANET has the requisite information to execute hypernode behavior in maintaining connectivity. An intelligent routing scheme that uses ad hoc routing techniques that take into account energy efficiency and link quality in establishing routes is the first part of the goal; the second part is establishing a case based reasoning scheme that takes into account specific routing environmental factors to determine the best routing scheme. Given this approach, the research methodology consists of three phases: the platform research and hands-on familiarization with the data and voice communication capabilities of the system, an analysis from a traditional network management perspective, and finally a determination of metrics and variables for routing approaches and cases.

A. THE TRELLISWARE CHEETAHNET II TW-230 RADIO

TrellisWare Technologies, Inc. is a privately held communications company headquartered in San Diego. Spun-off from ViaSat in April 2000, TrellisWare operates as an independent business focused on cultivating solutions for ground communications problems. Self-funded since its inception, TrellisWare specializes in advanced communication algorithms, waveforms, and turn-key communication systems (https://www.trellisware.com).

The TrellisWare CheetahNet radio system is a software-defined, barrage relay network of radios that incorporate autonomous cooperation, and physical layer switching to accomplish reliable communications in the harshest of radio-frequency (RF) environments (Halford & Chugg, 2010). The radio systems employ a Dynamic Network Architecture (DNA) at the Media Access Control Layer and above, implementing multiple protocol models that enable distributed control (Blair, Brown, Chugg, & Johnson, 2007). The system uses a time-division multiple-access (TDMA) method to maximize use of the available bandwidth; this function is enhanced by a Physical Layer (PHY) capability to combine a message sent by multiple sources as if they were sent by

one sender (Blair, Brown, Chugg, & Johnson, 2007). The performance specifications are in Table 1.

Features	Specifications
Transmit Power	2 Watt Peak (selectable 100 mW, 250 mW, 500 mW, 1 W, and 2 W)
Frequency Ranges	30 - 225 MHz, 225 - 512 MHZ, 1755 - 1815 MHz (3 segments); 2200 - 2270 MHz (4 segments
Relay Support[1]	Up to 8 hops for voice and data
Position Location[1]	Integrated GPS with stub antenna or powered patch antenna
Security[1]	AES-256 keys for each voice and data channel
Size (w/o accessories)	4.75" (H) x 2.63" (W) x 1.50" (D)
Weight	32 oz (R/T unit), 2 oz (sensor dongle)
Maximum Data Rate[1]	2.5 Mbps IP data rate @ 8 hops
Host Interfaces	Ethernet, Analog Video, Trigger In / Out
External Connectors	24-pin multifunction, 6-pin audio, TNC antenna, SMA GPS antennas
Environmental Compliance	Meets MIL-STD-810F with 2 meter immersion (R/T)
Input Power	6-18 Volts DC
Radio Configuration	Frequencies / crypto / network parameters / sensor settings from web application
Operator Controls	Volume on/off with zeroize, channel select, push button display menu controls
Data Types[1]	AMR 5.9 voice, IPv4 or IPv6 data, streaming video/audio
Video / Audio Encoding[1]	MJPEG with AMR for audio over voice channel
Audio Channels[1]	Up to 8 channels
Headsets	Peltor Comtac, Nacre QuietPro, Silynx, H-250, Clear Tone and settings for additional types
Audio Latency[1]	3 Hop < 250 ms; 8 Hop < 400 ms
Net Entry Time [1]	< 1 sec
Antenna	Support TNC connector non-power antennas for each freq band
Battery Run Time	1+ week continuous, 30+ days WoW, 10+ months WoT (on MBITR battery)
Occupied Bandwidth	4 to 20 MHz (TSM), 12.5 or 25 KHz (FM), 25 KHz (AM)
IP Support [1]	Full IP supports Unicast, Multicast, Broadcast and full TCP support
Power Conservation [1]	Wake-on-Wireless / Wake-on-Trigger / Active

Table 1. TrellisWare CheetahNet II TW-230 Technical Specifications (From TrellisWare Technologies, 2012c)

Reading about the specifications was not enough to fully understand the radio systems; hands-on time was necessary. With that in mind, multiple hours were spent in learning to setup and operate the radios. There were twenty four radios available from the CENETIX laboratory allocated for this purpose. The radio setup process is complicated; however, the process for setting up multiple radios is facilitated by their ability to be programmed simultaneously using a Cisco switch. Each radio is assigned a Class A network IP address with a network prefix of 10.1.XXX.XXX. In the true sense of classful addressing this is not a Class A address because only two octets are provided for the host addressing. The IP addresses for the radios used in the laboratory were already marked on each individual radio; if they were not, TrellisWare provides a method of determining the numbers in the last two octets in the MANET Mission Configuration (MMC) guide. When the radios are attached to the router, a laptop with an Ethernet connection can connect to all the radios via the Cisco switch. That occurs provided that the following conditions exist: the laptop's IP address for the Ethernet Network Interface Card (NIC) must be the same network address as the radios, the NICs subnetwork mask must be hard-coded in as 255.000.000.000, TrellisWare's default certificates must be installed in the Internet browser used to access the radio, and the radios must be placed in "programming mode."

After the completion of those prerequisites, one simply has to type in the IP address of one radio in an Internet browser to get access to the MMC. Figure 7 displays the options available to the user upon entering the IP address of one of the radios attached to the switch. There are multiple options including the Tactical Topology Viewer Controller (TTV-C) Network Utilization Matrix that will be discussed later. The MMC is the tool used by the network manager to perform initial setup of the radios that will be operating in the same network.

Figure 7. TrellisWare Web Application Screen (From TrellisWare Technologies, 2012b)

1. Mobile Ad-Hoc Network Mission Configuration Tool

The Mobile Ad-Hoc Network Mission Configuration Tool contains everything the network manager needs to perform initial configuration of the radios. Radio Configuration is based on five main areas: device configuration, communications security, wideband settings, narrowband settings, sensor settings, and gateway settings. The device settings allow the network manager to set parameters such as the power output, the node's alias (name), establish the type of power source used (battery versus direct connection to power source), GPS coordinate type (MGRS, UTM, Lat/Long, etc.), and many other factors. Even the type of headset used with the radio is configurable. The device settings tab on the MMC tool is shown in Figure 8.

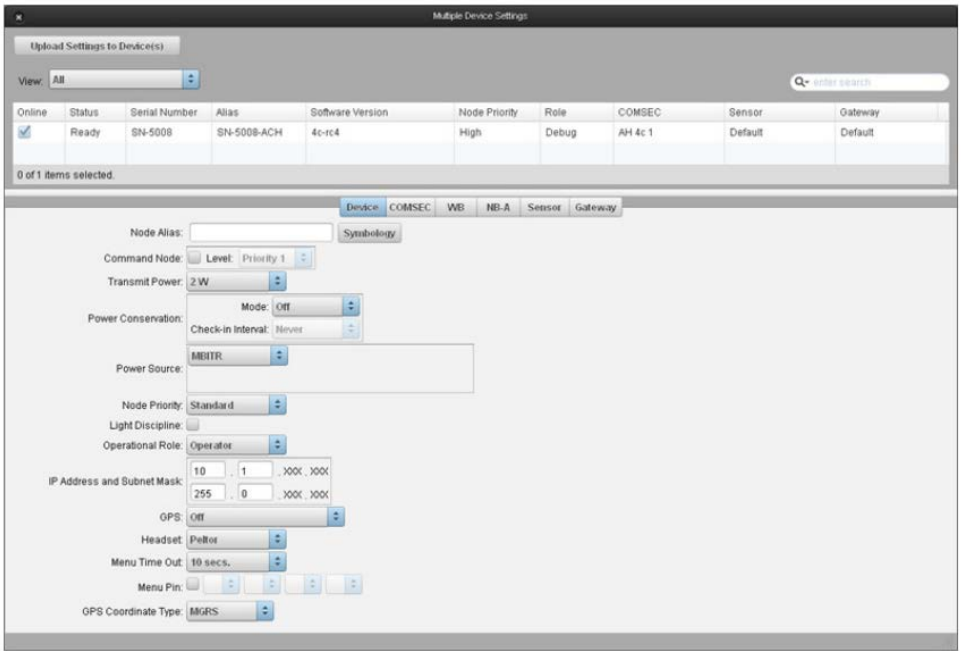

Figure 8. Device Settings Tab of MMC (From TrellisWare Technologies, Inc., 2012b)

The COMSEC Settings Tab is to import a communications security key onto the radios. The TrellisWare CheetahNet 230s utilize the AES-256 encryption standard in the generation and use of keys. The Wideband settings enable the network manager to set a center frequency and choose how the total bandwidth will be equally divided among channels, with the largest bandwidth per channel being 20 MHz.

The radios system allows the user to set the maximum number of hops for each individual channel; using this feature could lead to more effective frequency reuse. Given limited bandwidth, separate networks can use the same frequency band simultaneously if the preset maximum hop count is established in such a way so that messages cannot travel across those networks.

The Narrowband Audio tab allows a network manager to setup the radios for analog modulation of voice signals. It was not used during this research. The Sensor tab allows managers to configure the radios to connect to remote sensors. Gateway settings is another tool that allows the radios in the network to connect to another IP based network. One radio acts as the gateway; it maintains a Network Address Translation (NAT) table that maps the IP address of each radio to a unique port appended to the

gateway radio's IP address. The sensor settings and the gateway settings were not used in this research also.

2. Tactical Topology Viewer Controller

The TTV-C enables the network manager to monitor the performance of the network radios and to perform some limited network element management. The TTV-C allows the network Manager to (TrellisWare Technologies, Inc., 2012a):

1. See information on alerts--such as breaks in node links, and low battery levels
2. Visualize the locations of the network nodes on a map
3. See specific information on each node operating in a network, such as node aliases, IP addresses, MAC addresses, and GPS grid locations (if enabled)
4. Observe the quality of the links between nodes[3]
5. Perform over the air rekeying and zeroing (not used in this research)
6. Observe and configure remote media streams (not used in this research)

The Node List window is a subcomponent of the TTV-C tool that provides a lot of information, but only a few categories of information were useful to this research. That pertinent information included the status of each radio (active or inactive), the battery level, and the age (length of time since last update). A screenshot of the Node List window is shown in Figure 9.

[3] The nodes are projected onto a map, and their links are displayed as solid lines with link colors to indicate signal strength. There are four colors used to represent link quality: blue, green, yellow, and red. Blue represents the strongest link between nodes; red represents the weakest (TrellisWare Technologies, Inc., 2012a).

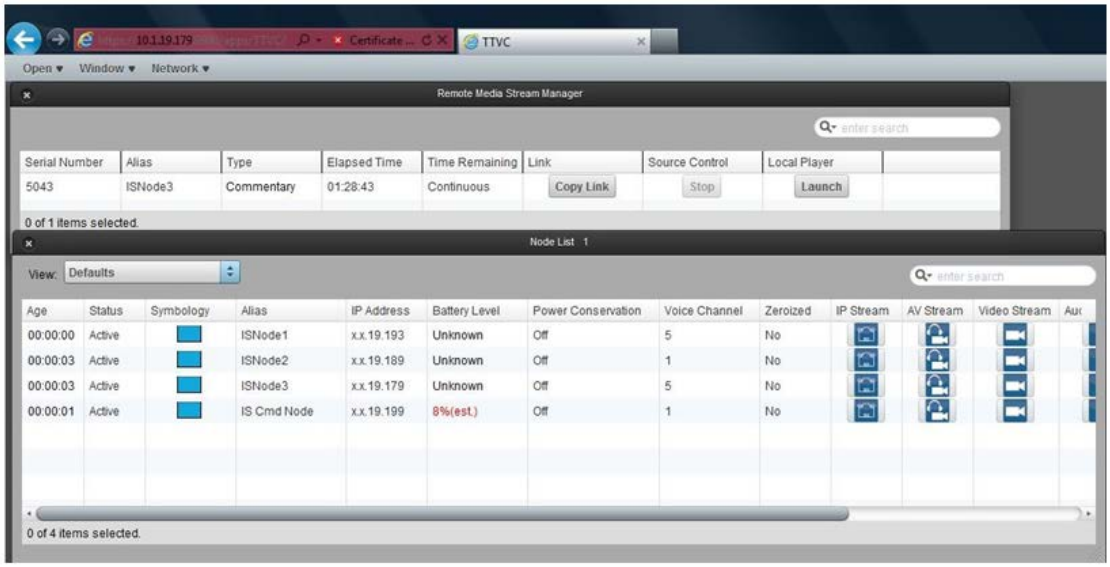

Figure 9. TTVC Node List and Remote Media Stream Windows

The Link List window is an invaluable subcomponent of the TTV-C: it shows the link quality of each connection between pairs of radios in the network. There are four colors to represent the quality of a link: blue (excellent voice and data quality), green (good voice and good data), yellow (good voice and acceptable data), and red (acceptable voice and poor data quality) (TrellisWare Technologies, Inc., 2012a). A screenshot of the Link List window is provided in Figure 10.

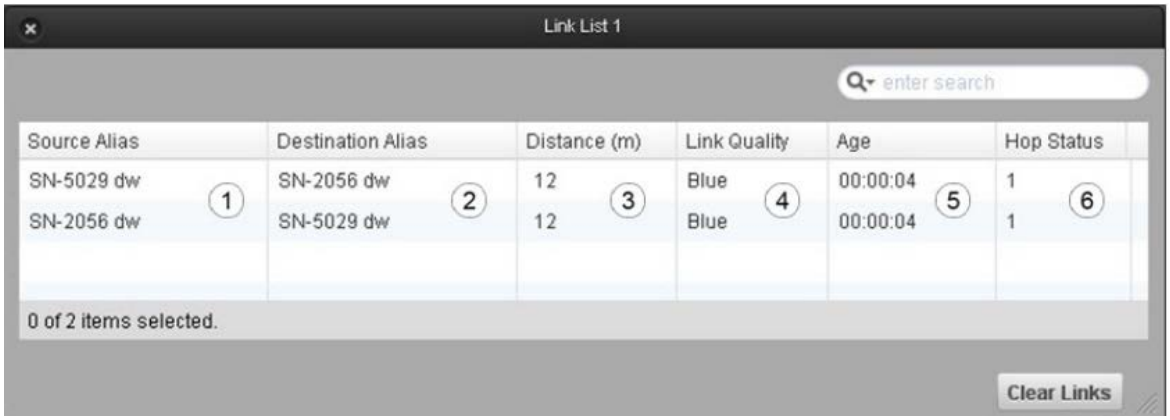

Figure 10. TrellisWare Link List Window (From TrellisWare Technologies, 2012a)

B. RESEARCH DESIGN

The Barrage Relay scheme incorporating TDMA gives the CheetahNet II TW-230 radios a great advantage in providing robust communications. The tradeoff for this capability is in spectral effectiveness and energy efficiency.

Barrage Relay causes nodes that are not linked between the source and destination node to unnecessarily forward messages, wasting output power. In addition, TDMA is a capable multiple access mechanism, but it does not adapt to changes in the quantity of active users.

The radio system's network management capabilities, when compared to the functionality described in the Telecommunications Management Network (TMN) model (Subramanian, 2010), allow for some modest configuration changes only at the network element layer. A more energy efficient paradigm would take into account the battery life of the individual nodes, and it would use only the necessary bandwidth resources when they are needed. A more spectrally effective paradigm would maximize the use of available bandwidth as necessary. Barrage Relay networks do not accomplish either for two main reasons: (1) Barrage Relay networks use every node to broadcast a message it receives, hence situations arise when nodes re-broadcast messages received that have no chance of getting to the intended destination through the intermediate node, and (2) Barrage Relay networks use Time Division Multiple Access (TDMA) to allocate each node time to broadcast its message. In the event that a network's node density is low, a large number of time slots are not being used for transmission or reception. Essentially, time is being wasted that could be allocated for message transmission.

An Ad Hoc intelligent routing scheme, when coupled with a case based reasoning system that takes into account specific factors in the scheme of maneuver represents a solid alternative to the Barrage Relay scheme. The Ad Hoc routing scheme requires a routing metric to evaluate possible routes for efficiency. A routing metric that takes into account both the battery life of the intermediate node and the SNR between links (both factors are equally weighted) is displayed in Figure 11. *SNR* represents the Signal to Noise Ratio of the Link between a transmitter and receiver expressed in decibels (dB).

Batt. Life represents the battery power remaining in the receiver node expressed as a percentage of a full battery.

$$LinkCost = \frac{1}{SNR} + \frac{1}{Batt.Life(\%)}$$

Figure 11. Link Cost for Ad-Hoc Routing Scheme

In this formula, links with a higher SNR and with a higher end node battery life will have a lower cost. The best route is the route where the sum of the link costs is least. Bourakov (2012) proved that it is possible to collect and display the SNRs of radios in a tactical environment using the HEAT Map interface to display collected JavaScript Object Notation (JSON) streams of data from CheetahNet 220 radios. An example of the output is shown in Figure 12.

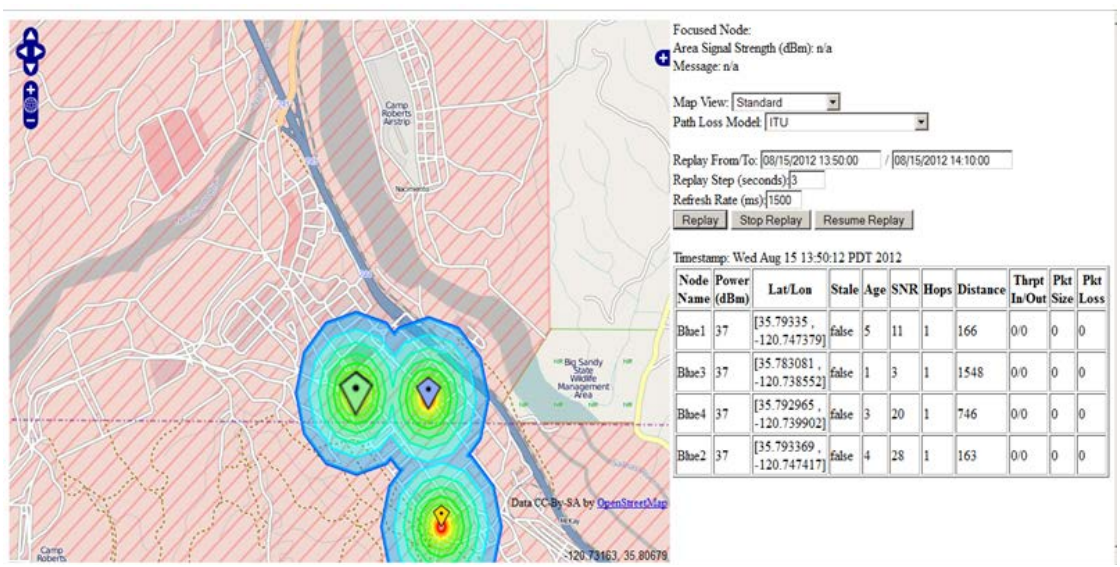

Figure 12. HEAT Map Interface (From Bourakov, 2012)

Stanley and Jeffords (2006) explain that in digital modulation schemes, there is a threshold SNR that is related to a desired Probability of Error (P_e). A generally accepted P_e for acceptable transmission and decoding of digital signals is 10-5, or one error in every 100,000 bits transmitted (Stanley & Jeffords, 2006). If the SNR drops below the threshold, then the P_e is not considered acceptable for data transmission. In that vein, it

would make sense to modify the equation in Figure 8 to account for the threshold SNR, termed SNR_t. The modified parametric model is shown in Figure 13.

$$LinkCost = \frac{1}{SNR - SNR_t} + \frac{1}{Batt.Life(\%)}$$

Figure 13. Link Cost Equation that takes into account threshold SNR.

TrellisWare also produces a full Web Services Application Programming Interface guide that allows developers access to network status information transmitted among the radios (TrellisWare Technologies, Inc., 2011). With a working knowledge of the Bayeux asynchronous message transmission protocol, a programmer or developer could extract from the individual radios information regarding the status and location of individual nodes, the status of links, and the status of streaming data (TrellisWare Technologies, Inc., 2011). The types of information that can be extracted are listed in Figure 14.

Asynchronous Node Content Message Content	Asynchronous Link Message Content	Asynchronous Event Message Content

PLI Node Message
Unit ID
Base URL
Location
  Age
  Latitude
  Longitude
  Altitude
  Heading
  Speed
  Climb
  Horizontal Position
  Uncertainty
  Vertical Position Uncertainty
Status
  Age
  Alias
  Voice Channel
  Zeroized
  Battery Percent
  Serial Number
  Sleep Mode
  Check-in Interval
  Healthy
  Stream Configuration
  IP Device ID0
  Audio Video ID0
  Video ID0
  Audio IP ID0
  Audio Voice Channel ID0
  Trigger Out ID0
  Power Out ID0
	PLI Link Message
	Age
	Source ID
	Destination ID
	Link Quality
	Distance
	Distance Quality
	Error Estimate
		Event Message
		ID
		Device ID
		Serial Number
		Alias
		Stream Type
		Initiator
		Error Code
		Error Message
		Start Time
		End Time
		Current Time
		Video Width
		Video Height
		Poster File
		SDP File
		RTSP Port
		GPS Location
		Voice Channel

Figure 14. TrellisWare Asynchronous Node, Link and Event Content available (From TrellisWare Technologies, 2011)

In the discussion of Ad-Hoc routing schemes, Kiourmourtzis (2005) noted that there was no one best routing scheme: certain schemes were better suited for specific situations. These situations can be used as a basis for building the cases in a case based reasoning application. Given the increased overhead of proactive routing protocols, it makes sense to opt for a reactive protocol. Based on Kourmourtzis' (2005) observations, two attributes of a case are readily apparent: node density and node mobility. Given the two attributes, there are four possible outcomes based on the cases: high node density/low network mobility, low node density / low network mobility, low node density / high network mobility, and high node density / high network mobility.

For these cases to work there must be distinguishing factors between high and low node density and network mobility. Kourmourtzis' (2005) research establishes a threshold of 90–100 nodes to distinguish between the AODV and DSR routing protocols;

based on his observations the lower threshold of 90 nodes can represent the boundary between high and low node density. Mobility is not as clearly defined; this threshold can be determined by examining the tactical use of these radios. At the tactical level, combatants are either foot mobile or on vehicles. Personnel on foot cannot be expected to travel faster than 15 miles per hour for extended periods, and that is a high threshold, which would equate to a combatant moving at a four-minute-per-mile pace. Therefore, nodes moving at speeds higher than 15 miles per hour (MPH) would be considered highly mobile.

A tactical network will consist of multiple nodes operating at different speeds. In order to accommodate that fact, it makes sense to look at the aggregate speed of the nodes in the network when considering the criteria for CBR cases. A network where a simple majority of nodes are operating at or above the threshold of 15 MPH can therefore be considered highly mobile. Given the thresholds to distinguish network mobility and density levels, two cases are readily apparent. In the case of high network density, and low network mobility, it has been shown that AODV is the optimal protocol (Kiourmourtzis, 2005). In the case of low network density and high network mobility, DSR is the optimal protocol (Kiourmourtzis, 2005). OLSR is suitable for low density networks in general (Kiourmourtzis, 2005). A basic case structure showing ad hoc routing schemes and optimal conditions for employment based on Kiourmourtzis' results is shown in Table 2.

Density / Mobility	High	Low
High	AODV	OLSR
Low	Unknown	DSR / OLSR

Table 2. CBR case structure based on mobility and node density factors.

A link cost routing metric used to determine the best route between a source and destination in ad hoc routing would incorporate two metrics: SNR and receiver battery life. Since it has already been shown that the SNR of a given signal can be determined

(Bourakov, 2012), the next step is to determine the threshold SNR for effective data transmission. TrellisWare uses a link color scheme to depict the quality of link between two nodes. Blue represents a link that is excellent for voice and data transmissions; green represents a link that is capable of good voice and data quality; yellow represents a link that has good voice quality and acceptable data quality; red represents a link that has acceptable voice quality and poor voice quality (TrellisWare Technologies, Inc., 2012a). The cases used to determine the best routing protocol for a particular situation also provide variables that can be measured: node rate of movement (or speed), and node density. Measuring these variables is the basis for the proof of concept.

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IV. EXPERIMENTATION AND RESULTS

The data for this thesis comes from two major test events. The first testing event occurred at Camp Roberts, California. Data was collected from the operational testing of the CheetahNet II TW-230 radios in a tactical scenario. The second testing event was designed to collect and evaluate data collected from a tactical scenario conducted on the grounds of the Naval Postgraduate School and in the local area surrounding it.

A. ENHANCED MAGTF OPERATIONS LIMITED OBJECTIVE EXPERIMENT 3

The Marine Corps Warfighting Lab (MCWL) has been performing experiments to develop the MAGTF's ability to conduct Distributed Operations (DO) (Marine Corps Warfighting Laboratory, 2013). The CMCs guidance in the Marine Corps Vision and Strategy 2025 (Conway, 2008) is the driving force behind MCWL's research in Enhanced MAGTF Operations (EMO). The strategy document directs the Marine Corps' research organizations to "aggressively experiment with and implement new capabilities and organizations" (Conway, 2008). The organizational structure and doctrine of the MAGTF is changing such that capabilities previously believed to be only effective using an infantry battalion (the Battalion Landing Team or BLT) can now be performed by a company sized force (the Company Landing Team or CLT). LOE 3 is the result of the evolution of the EMO experiments, building off previous DO, ECO, and EMO experiments. EMO LOE 3 focuses on the fires aspect of EMO, whereas LOEs 1 and 2 focused on command and control and logistical support of EMO.

The goal of EMO LOE 3 was to create a synergy of fires on the distributed battlefield. The experiment was built around the hypothesis that the effectiveness of Fire Support for a sea-based force can improve dramatically with the right equipment (e.g., over-the-horizon (OTH) coordination and communications suites) and the training of key personnel. The sea-based Fire Support organization in this experiment was the Supporting Arms Coordination Center, responsible for integrating and managing supporting fires during the initial landing of an amphibious force. Based on these

concepts, EMO LOE 3 was conducted from 9-19 May 2013. It assessed the capabilities and Tactics, Techniques, and Procedures (TTPs) of MAGTF Fires using a combination of current and newly developed technologies.

1. Concept of Employment

The Concept of Employment centered on a Mechanized/Motorized Company Landing Team (CLT) and a Helo-borne CLT conducting an attack on two battalion objectives. For this experiment, it was assumed that the ship-to-shore movement had already occurred for both landing teams. Each CLT's task organization included two Fire Support Teams (FiSTs) and a company Fire Support Coordination Center (FSCC). The Helo-borne CLT had an Expeditionary Fire Support System (EFSS) (120mm Mortar) platoon attached, and the Mechanized/Motorized CLT had a M777 Towed Artillery platoon attached. The FiSTs were tasked to prosecute planned targets and targets of opportunity during the operation. The FSCC coordinated the employment of organic fire support assets and supporting assets (e.g. Close Air Support). The Supporting Arms Coordination Center (SACC) coordinated the employment of MAGTF Fires (e.g., HIMARS and Naval Gunfire) into the scheme of maneuver. The TrellisWare CheetahNet II TW-230s were employed at the company level, providing intra-company communications between the company FSCC, the FiSTs, and the weapons system platoons (i.e., EFSS and M777). The Aerial Mobile Ad Hoc Networking Passive Relay (AMPR) was utilized as a redundant relay for intra-company digital communications. The AMPR is a small unmanned aerial system that houses the TrellisWare CheetahNet CUB TW-400[4]. The AMPR's objective was to fill in coverage gaps—e.g., breaks in communication caused by terrain masking—to maintain a continuous network access. This solution was designed to prevent single nodes or groups of nodes from being isolated or disconnected from the main company network. Figure 15 provides a graphic depiction of the scheme of maneuver.

[4] The TrellisWare CUB TW-400 is similar to the TW-230 radio system, but it has a smaller form factor. It uses TrellisWare's Tactical Scalable MANET Enhanced (TSM-E) waveform, and is capable of encoding analog voice signals. For more information, see https://www.trellisware.com.

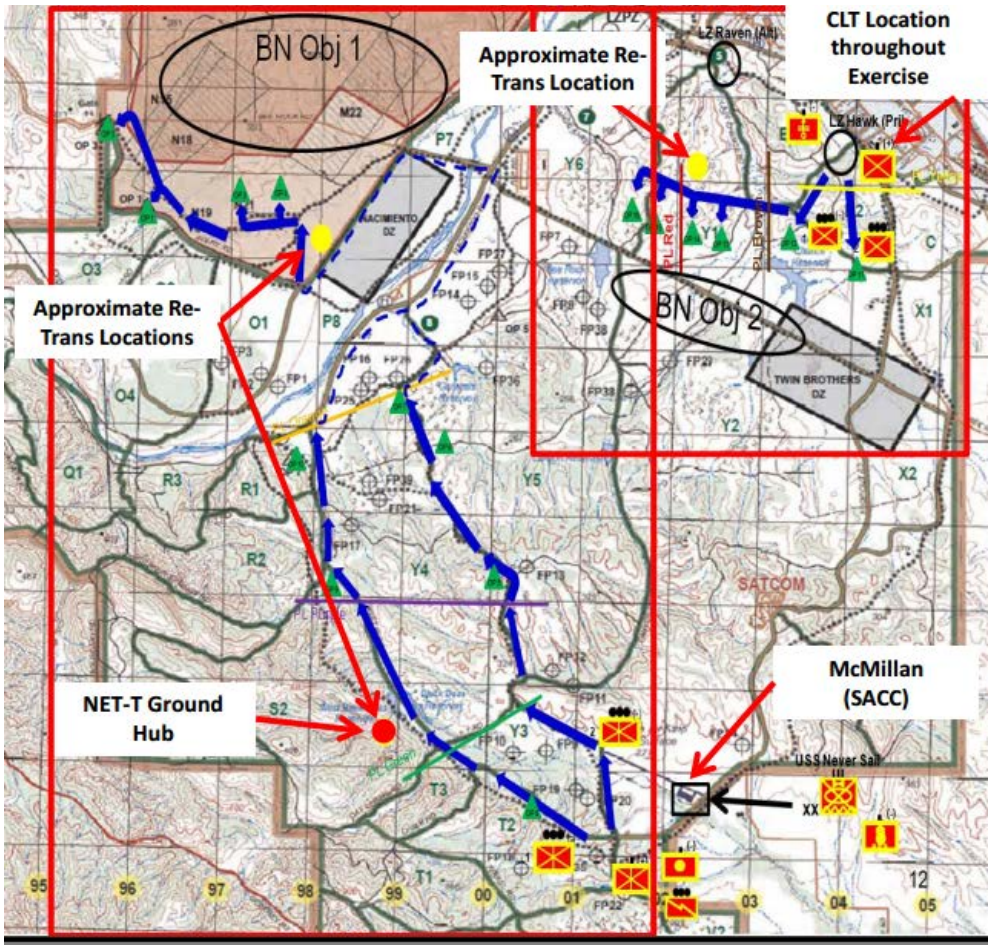
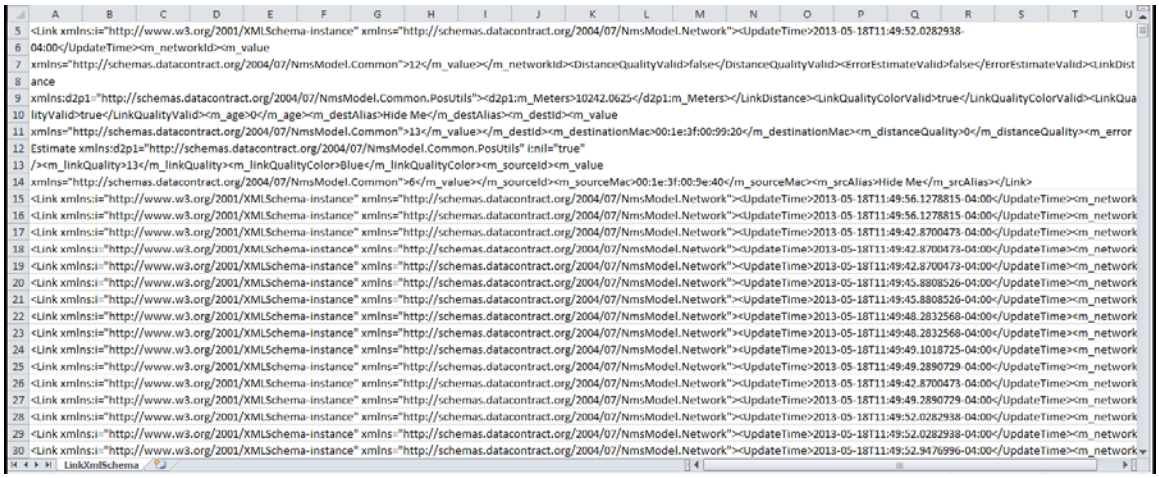


Figure 15. EMO LOE 3 Scheme of Maneuver (From Marine Corps Warfighting Lab, 2013)

2. LOE 3 Results and Data Analysis

The purpose behind this part of the experiment was to either confirm or deny that there is a direct correlation between the link quality of a connection amongst a node pair and the link quality color found in each radio system's position location information. Although seemingly a manifest conclusion, it still had to be confirmed due to the complexity of the technology that makes the TW-230s work. During one day of training, the Marine Corps Warfighting Lab was able to collect over 15,000 radio overhead messages using TrellisWare's Web Service API. Professor Huffmire from the Cyber Academic Group generated a .java file to parse out the extraneous information, leaving on the link quality and link color associated with each link message. Figure 16 and 17

respectively show a Microsoft Excel view of the unparsed data, and the resultant refined data after processing by professor Huffmire's parsing program. All original data points remained after parsing. The parsing program's code is provided in Appendix A.



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6  04:00</UpdateTime><m_networkId><m_value
7  xmlns="http://schemas.datacontract.org/2004/07/NmsModel.Common">12</m_value></m_networkId><DistanceQualityValid>false</DistanceQualityValid><ErrorEstimateValid>false</ErrorEstimateValid><LinkDist
8  ance
9  xmlns:d2p1="http://schemas.datacontract.org/2004/07/NmsModel.Common.PosUtils"><d2p1:m_Meters>10242.0625</d2p1:m_Meters></LinkDistance><LinkQualityColorValid>true</LinkQualityColorValid><LinkQua
10 lityValid>true</LinkQualityValid><m_age>0</m_age><m_destAlias>Hide Me</m_destAlias><m_destId><m_value
11 xmlns="http://schemas.datacontract.org/2004/07/NmsModel.Common">13</m_value></m_destId><m_destinationMac>00:1e:3f:00:99:20</m_destinationMac><m_distanceQuality>0</m_distanceQuality><m_error
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13 /><m_linkQuality>13</m_linkQuality><m_linkQualityColor>Blue</m_linkQualityColor><m_sourceId><m_value
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28 <Link xmlns:i="http://www.w3.org/2001/XMLSchema-instance" xmlns="http://schemas.datacontract.org/2004/07/NmsModel.Network"><UpdateTime>2013-05-18T11:49:52.0282938-04:00</UpdateTime><m_network
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```


Figure 16. Sample of Unparsed Data from LOE 3 Experiment

Link Quality (dB)	Link Color	Link Color Value
3	Red	1
42	Blue	15
5	Yellow	5
39	Blue	15
13	Blue	15
12	Blue	15
8	Yellow	5
7	Yellow	5
30	Blue	15
18	Blue	15
15	Blue	15
26	Blue	15
21	Blue	15
10	Green	10

Figure 17. Sample of Refined Data Showing Link Quality and Link Color

To quantify the qualitative link color data, an integer was assigned to each color (as depicted in Figure 17). The red link color was assigned the value "1", yellow was

assigned “5”, green was assigned “10”, and blue was assigned the value of “15”. That refined data with numerical equivalents was imported into MATLAB and sorted according to link quality, from lowest to highest. After sorting, the link quality numerical value (independent variable) was plotted versus the link color value (dependent variable). It is evident from the resultant plot in Figure 18 that there is a direct correlation between link quality (SNR in dB) and link color. It is also apparent from the data that there are clear link quality thresholds between each color. The data shows that the steep inclines in Figure 18 should actually be vertical lines because the link color value (and corresponding link color), upon reaching a certain link quality threshold level, “jumped” to the next higher link color level. The thresholds between link colors are as follows (format: “lower color – higher color” according to SNR): green-blue, 11 dB; yellow-green, 9dB, red-yellow, 4dB. Any SNR less than 4dB corresponded to the red link color, and an SNR that was 11 dB or greater corresponded to the blue link color. The highest SNR observed was 53 dB; the lowest was -2 dB. The most important threshold observed is the red-yellow SNR (4dB). This SNR represents the critical minimum threshold SNR (i.e., SNRt) needed in the link cost routing metric shown in Figure 12; without it, the metric would not be feasible because there would be no way to ensure robust data communications using the routing metric.

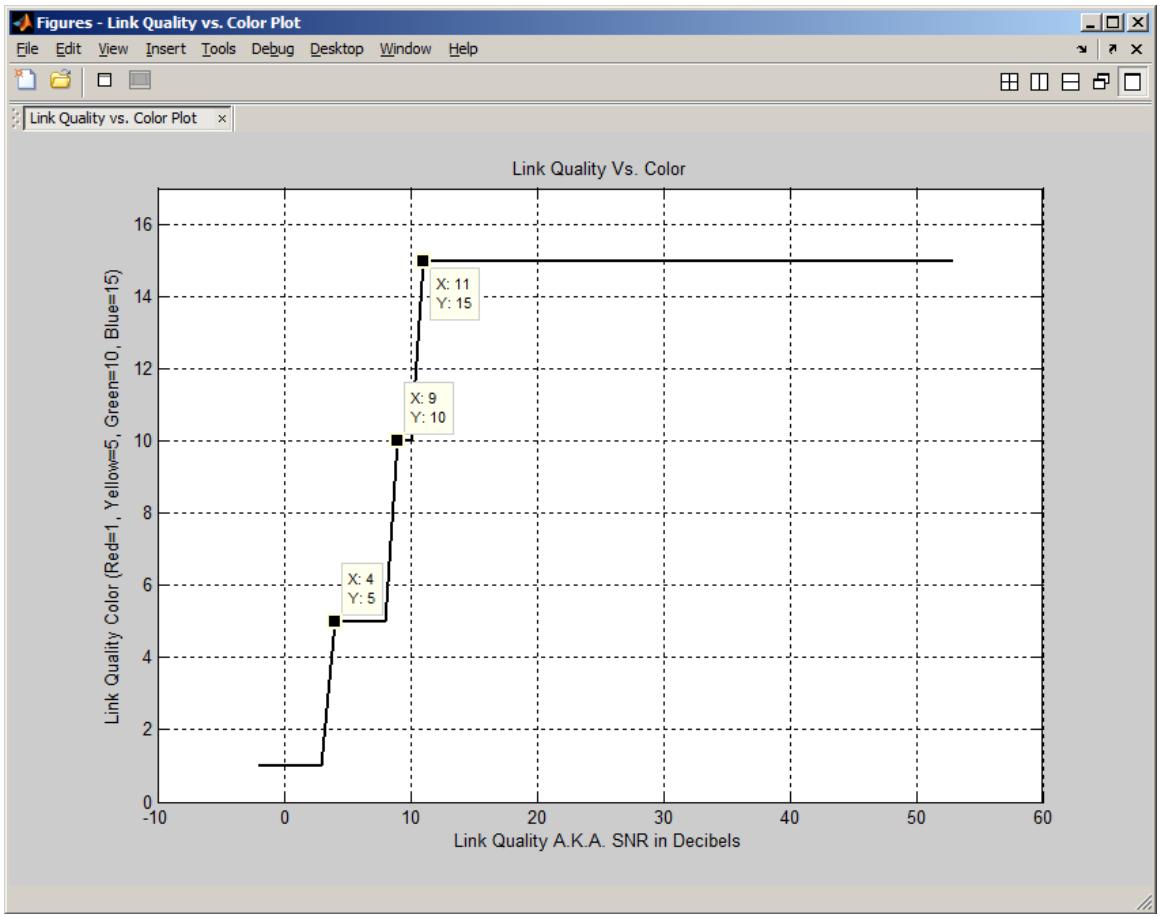

Figure 18. Link Quality vs. Link Color Value Plotted using MATLAB

B. NPS EXPERIMENTATION

1. Concept of the Experiment

The purpose of the NPS experiment was to gather data collected from the TrellisWare's data capture tool, which collects overhead message traffic information transmitted by the radios during operation. The experiment specifically assesses the ability to capture speed and battery power levels as advertised. The experiment was conducted in three phases. Table 3 shows the initial settings for the Trellis Ware radios used in this event.

Center Frequency	1785 MHz
Bandwidth	10 MHz
Power Output	2W
Power Conservation Mode	Off
Comsec Settings	MMC Keyring Generator created
Available Data Rate	540K / 8.75Mbs
GPS	Enabled
Software Version	4d-beta safe-zeroize
Voice Channels	1

Table 3. Radio Initialization settings for experiment

The first phase involved the setup and initialization of the radios for operation. A total of eight TrellisWare radio nodes were used in the experiment. The second phase involved operating the radios under normal loads in a small town tactical scenario. The second phase consisted of a foot patrol on the NPS grounds, followed by a vehicle patrol on the NPS grounds and in the surrounding area of Monterey, California. The purpose of the second phase was to evaluate the capability of the radios to accurately determine node speeds. To maintain a constant stream of data, relay nodes were placed on the roof of Spanagel Hall, The Del Monte Hotel, and Glasgow Hall before the foot and vehicle patrols commenced. The relay nodes, foot patrol, and vehicle patrol routes are depicted in figures 19, 20, and 21

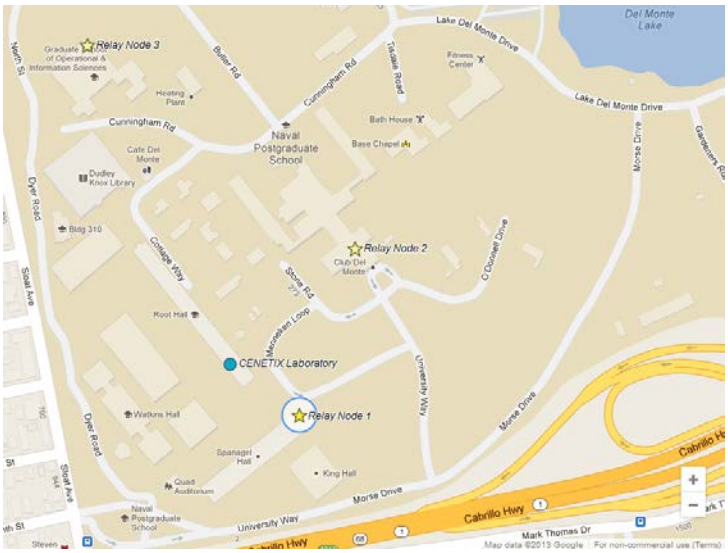

Figure 19. Stationary Locations: CENETIX Laboratory, Relay Nodes 1, 2, and 3. (created using mapsengine.google.com)

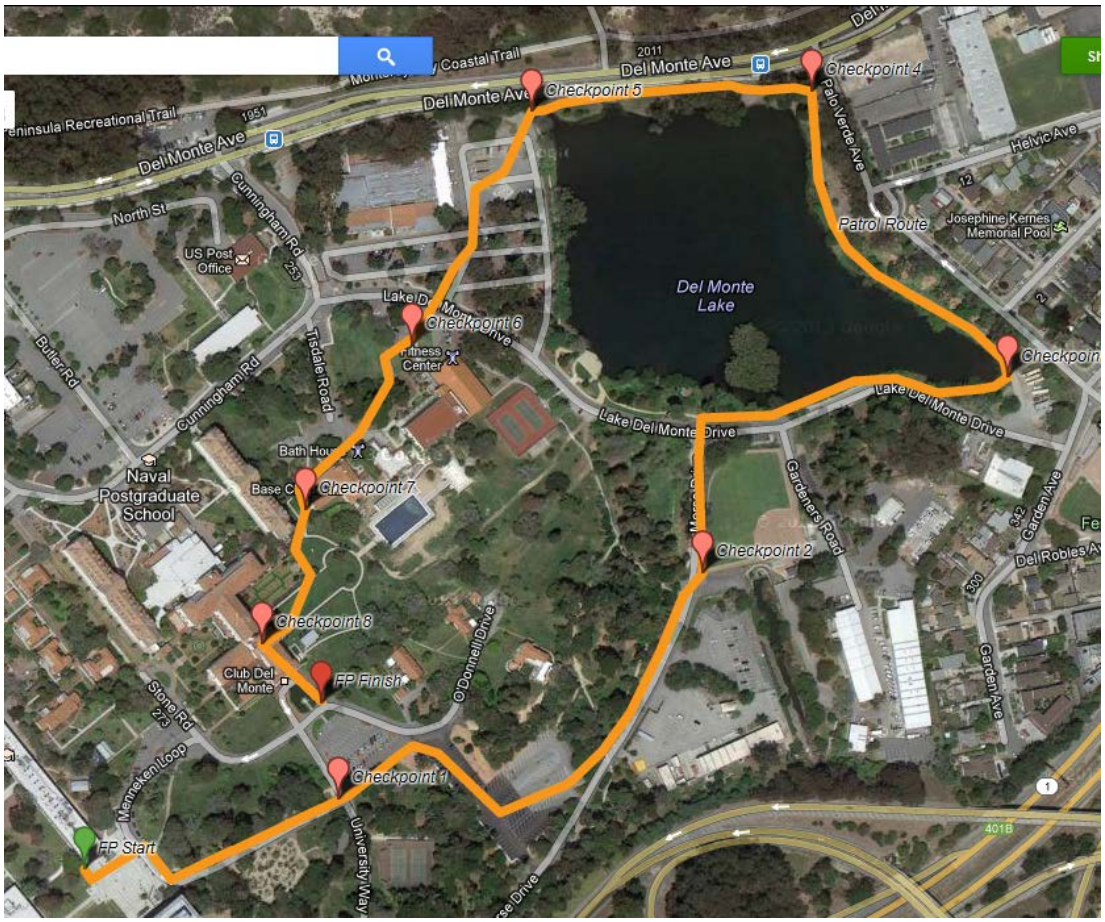

Figure 20. Foot Patrol Route (created using mapsengine.google.com)

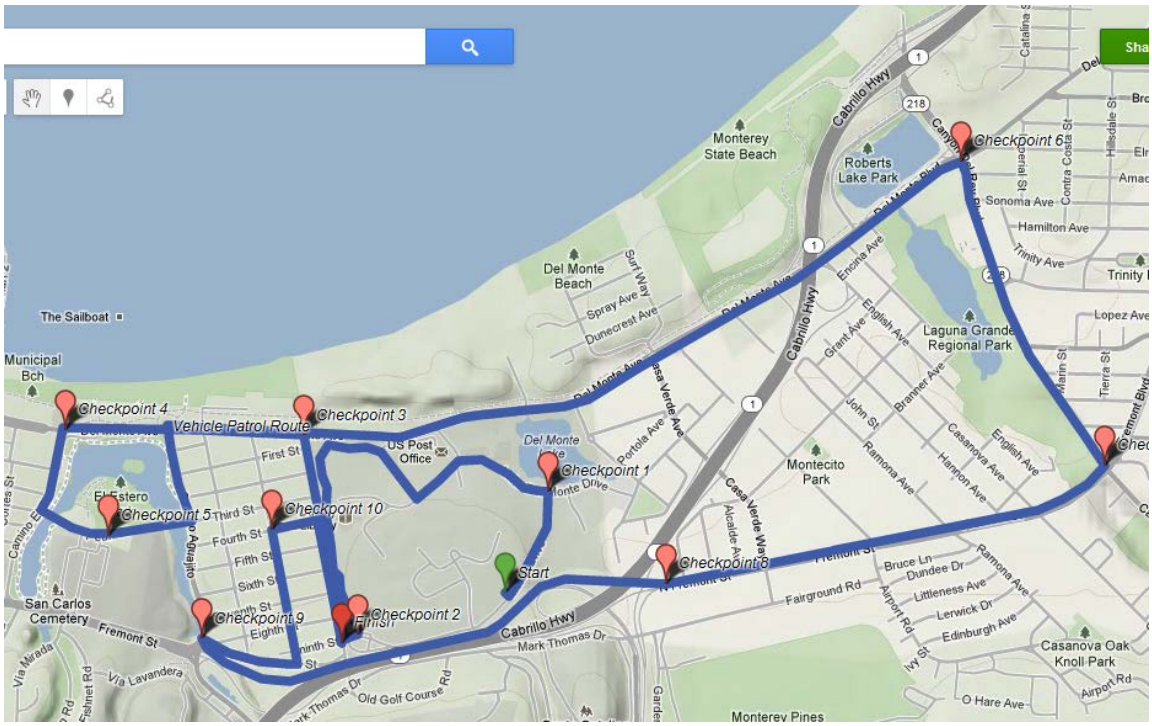

Figure 21. Vehicle Patrol Route (created using mapsengine.google.com)

In the CENETIX lab, two TW-230s were operated. One functioned as the Combat Operations Center (COC) node connecting a laptop running the TTV-C and the data capture tool to the rest of the network . The data capture tool allowed continuous logging of overhead information sent among the radios in accordance with the Web Services API. The second radio was connected to a standalone laptop running the Jperf streaming data simulation software. Three personnel were used in the conduct of the experiment; one to run the COC in the CENETIX lab, and the other two conducted the foot and vehicle patrols together. Each member of the patrol was assigned a radio; in addition, one member was given a Garmin Forerunner 10 GPS watch to verify the movement rate of the patrols. Following the foot patrol the vehicle patrol was conducted with no lapse in data collection from the radios.

The final phase involved determining the accuracy of the battery percentages as displayed on a radio. Two TW-230s were used in this experiment. A calibrated multimeter was used to independently verify the battery readings. The test battery was charged to full capacity (as indicated by a green light on the charging device), and the

battery voltage across its leads was measured. To confirm the reported full charge, the battery reading on the display of the connected radio was recorded also. The test battery and radio was then connected to a Panasonic Toughbook running the Jperf software in server mode. A separate computer running Jperf in client mode was connected to a second TW-230 radio. The experiment was setup so that a constant stream of data was sent from the Jperf server through the test radio/battery combination to the destination radio running the Jperf client. At regular intervals, battery readings were taken recorded the radio screen, and separately using the multimeter. After each reading, a ping test was conducted from the client computer to the server computer to ensure a complete network connection was present before continuing the streaming data connection. Readings were recorded until the battery would no longer power on using the test battery.

2. Urban Patrol Results and Data Analysis

The foot and vehicle patrols yielded no results for node speed in both scenarios, despite the nodes having solid GPS fixes. This was verified in the data results captured by the TrellisWare data capture tool. On both the TTV-C interface and in the data capture tool logs, no speed was recorded. The source of this error is unknown at this time. Over 6000 data points were captured in the combined foot and vehicle patrol log; any messages that did not contain a GPS location were discarded, resulting in 3500 solid data points for analysis. This is considered acceptable because of the total number of TrellisWare radio nodes two did not have GPS turned on or antennae attached; furthermore other data points that did not have a good GPS fix. Of the remaining nodes with a good GPS fix, no speed other than zero was shown on the TTV-C. This was confirmed by the data results captured by the TrellisWare data capture tool. On both the TTV-C interface and in the data capture tool log files a speed of “0.0” mph was recorded for every data point. This contradicts the accounts from both patrol members, and the output of the Garmin Forerunner 10. The graphs of the speed versus time output for both patrols as collected from the Garmin are depicted in figures 22 and 23.

Figure 22. Garmin Forerunner 10 Speed vs. Time Graph for Foot Patrol (from connect.garmin.com)

Figure 23. Garmin Forerunner 10 Speed vs. Time Graph for Vehicle Patrol (from connect.garmin.com)

From both graphs the maximum speed can be observed. According to the data collected from the Garmin, the maximum speed of the foot patrol was 15.9 miles per hour (a very fast sprint that lasted for less than a second), and the maximum speed of the vehicle patrol route was 49.9 miles per hour. The TrellisWare radio's recorded speed of "0.0" mph was inaccurate based on the account of the patrol members and the Garmin's GPS data. TrellisWare Industries, Inc. was contacted to troubleshoot this issue. A senior product manager from the company stated that the ability to capture speed was not yet offered in the web services API for the current software version (e.g., software version 4d). It was also observed that during the vehicle patrol, all communications were lost

between the COC in the lab and the patrol members in between Checkpoints 6 and 7; this was documented in a screen capture of the TTV-C application, shown in Figure 24.

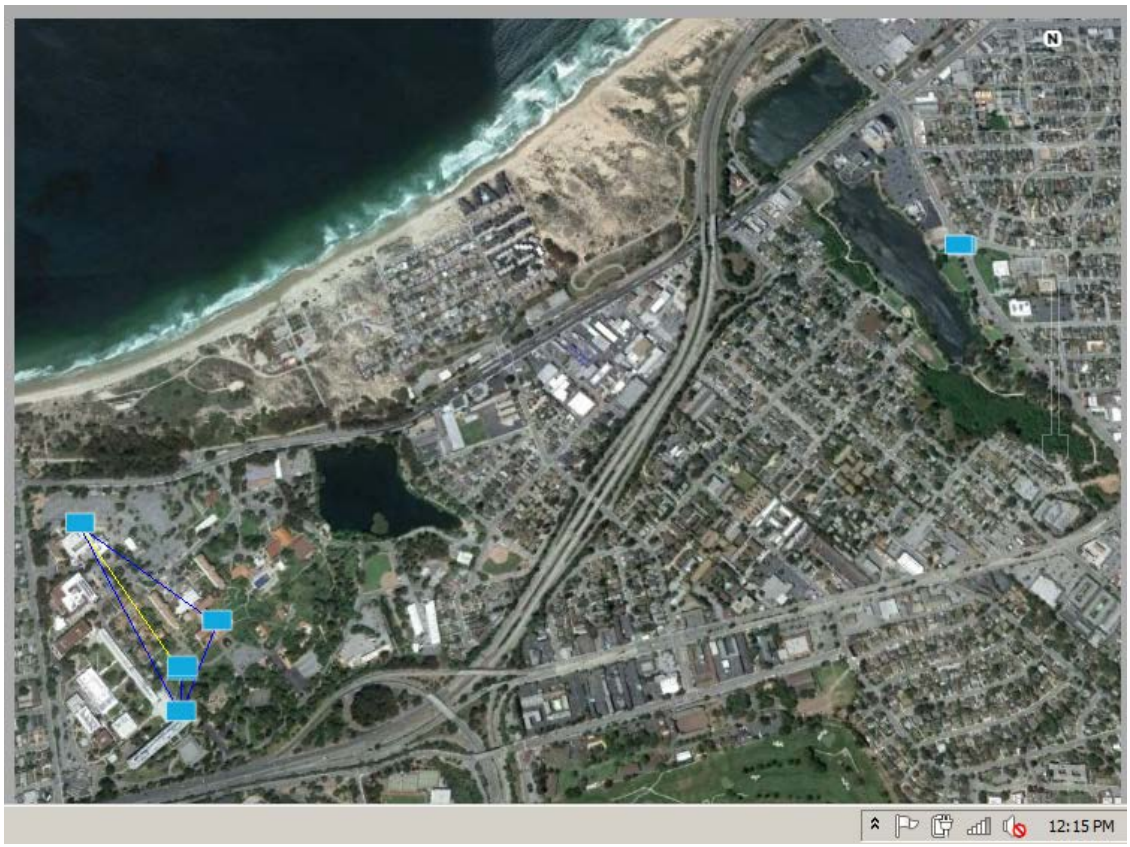

Figure 24. Last known Position and Contact with Vehicle Patrol unit

The two radio nodes conducting the vehicle mounted patrol never rejoined the original network even when the patrol was completed and the two nodes were physically located adjacent to the command node in the COC. This was an alarming and unexpected result; given the literature, it was expected that the radios would self-heal once within range of the original network. After a hard shutdown and restart of the two radio nodes, the nodes then rejoined the network.

3. Battery Testing Results

The results of the battery test when compared with the multimeter readings yielded conflicting results. To convert multimeter readings into percentages, the formula

for interpolation was used, with the maximum value being the first voltage reading (12.34 Volts), and the minimum reading used was the highest of the voltage readings that corresponded to “0%” on the radio display (10.88 Volts). One may observe from the data that there was a range of voltage readings that corresponded to “0%” on the radio display. At each 0% reading (with the exception of the final reading at 484 minutes elapsed), the radio would either conduct a self-restart (observed at 18:33 and 18:36), or it was restarted manually (executed from 458-481 minutes elapsed). The maximum “0%” reading was chosen because any reading less than that reading would not be sufficient for communications due to the fact that the radio would self-restart at any of the “0%” values. After conversion of the voltmeter readings to percentage values, the calculated battery percentage was compared to the displayed battery percentage using the deviation formula in Figure 25.

$$\%Deviation = \frac{Observed - Actual}{Actual} * 100$$

Figure 25. Formula for Percent Deviation

It is important to note what was considered the “observed” and “actual” values. The observed values were values read from the radio display, and the actual values were values taken with the multimeter. The reason these values were deemed as such and not vice versa is because the zero percent reading on the radio display did not really mean the battery was fully discharged. In actuality there was still a large amount of charge left on the battery when the display read “0%.” Discounting the negative percentage deviation values that correspond to battery voltmeter readings less than the highest recorded “0%” value of 11.88V, the average percent deviation was 22%, with the highest deviation being 46% (241 minutes elapsed). On the second run, the maximum and minimum voltages recorded were 12.36V (start) and 10.84V (497 minutes elapsed). The highest deviation recorded was 52% (at 481 minutes elapsed). The plots of time elapsed versus percentage deviation are shown in figure 26. Although the two plots show consistent deviation curves, the maximum deviation percentage occurs at different points on each curve; the

highest deviation for the first run occurs toward the middle of the test, whereas the highest deviation for the second run occurs towards the end of the test.

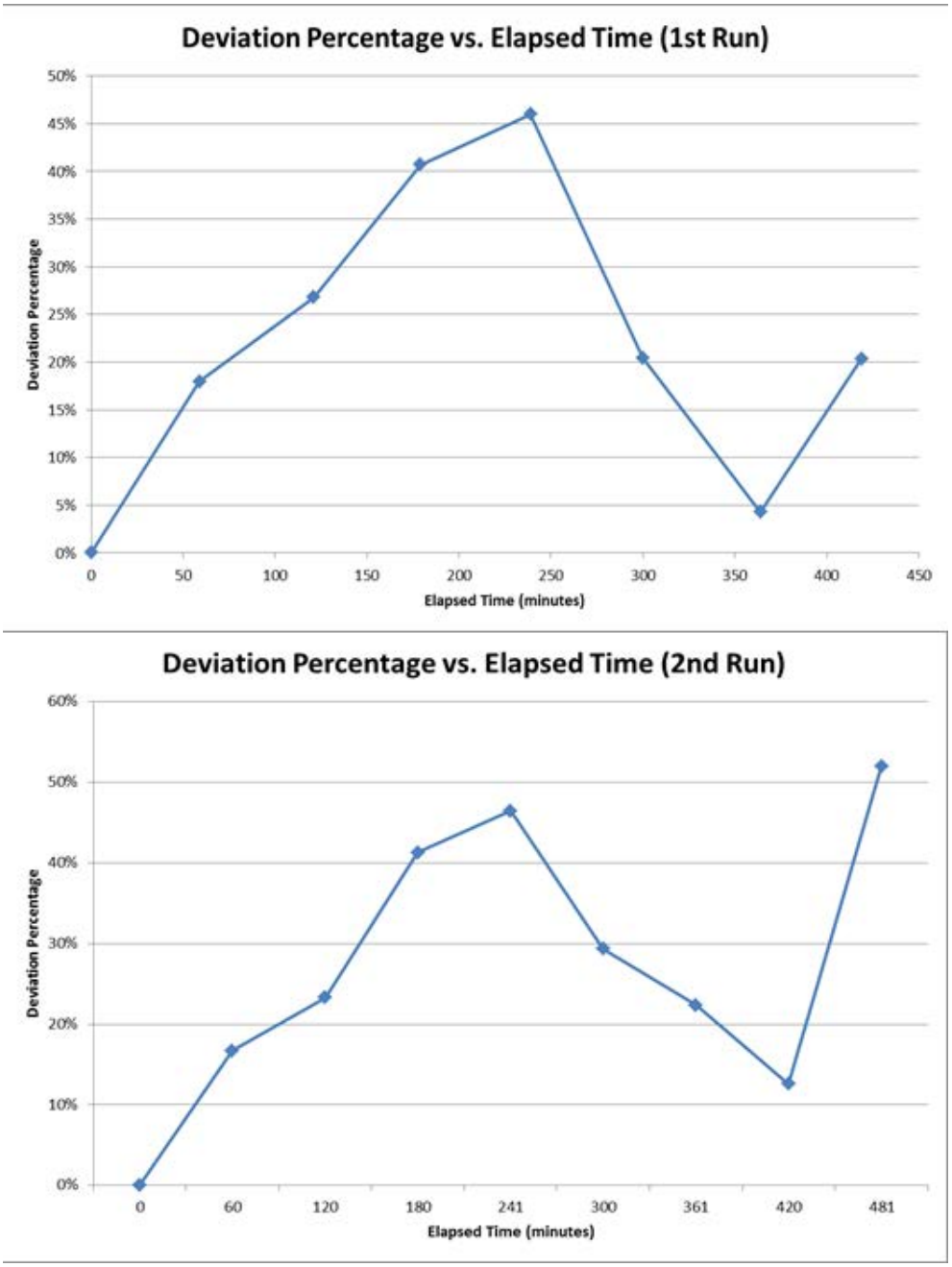

Figure 26. Battery Test Results In Microsoft Excel

The implications of the battery test results specifically impact the accuracy of the routing metric; it is extremely important in determining the most efficient route. The battery test conclusions regarding accuracy would have more weight if more iterations were conducted with different radios and batteries.

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V. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This research started out with a couple of goals in mind that were centered on the necessary management tools to ensure that MANETs are able to support tactical communications that are critical to the Marines Corps vision of future combat operations. The main goal was that was developing a routing metric to evaluate alternate MANET routing schemes. That metric was developed through a thorough review of the literature and analysis of Marine Corps future communications requirements. This research attempted to collect the necessary information needed to demonstrate that the routing metric data was available. The routing metric is important for determining the cost of any given route between the source and destination in a MANET, hence a vital piece of information for using the most efficient route—a key element to mitigate the constraints imposed by mobile, battery operated tactical radios. With that information, a discussion of the benefit of different Ad-Hoc intelligent routing approaches was presented. A case based reasoning approach was then put forth to exploit the potential that hypernodes portend to the management of MANETs.

A. CONCLUSIONS

The conclusions of this thesis are developed from the investigation into the following research questions. Each subsection below briefly explains the key rationale for the question, the findings, and their implications to this, and future, research. .

What are the relevant factors in establishing the cost of each link for a given route between a source and destination?

The research reviewed in Chapters II and III proffers that when operating in a bandwidth and energy constrained environment, it is important that an intelligent routing scheme accounts for the SNR, the minimum threshold SNR for transmission of digital signals, and the battery life of the destination node in a link, for bandwidth effective and energy efficient transmissions. These findings are important because it provides a foundation for alternate routing methods. Recommendations for further research would

involve using the aforementioned routing metric to determine the route cost between a given source and destination in a MANET.

Can those factors be measured?

From the experimentation, the SNR between a link pair could be obtained from the position location information in the overhead transmissions among the radios. It is recommended that further research be conducted to verify the accuracy of SNR's presented by the radio system. The remaining battery percentage of a particular node was also observed among the overhead messages logged by the data capture tool. The ability to measure these factors allows a user or automated system to implement any ad hoc routing algorithm. It is recommended that future research is conducted to validate the accuracy of battery information obtained by the data logger tool. That research would involve multiple iterations with different radios employing a combination of voice and data transmissions in multiple environments.

How can a case-based reasoning (CBR) approach be applied to maximize the effectiveness of an intelligently routed MANET?

From the research in Chapters II and III it was determined that due to the highly dynamic topology of the nodes in MANETs, multiple routing schemes should be implemented because—to date—no one routing scheme has been shown to be optimal in all conditions of dynamic MANETs. There is a tradeoff associated with each available MANET routing scheme—i.e., each routing scheme performs differently depending on network node density and aggregate node mobility levels. Based on the environment and operational characteristics of the nodes in a MANET, a hypernode could determine the optimal routing approach to be used, maximizing the effectiveness of the network in multiple situations. That determination by the hypernode is contingent upon the collection of accurate node density and speed information, and the classification of aggregate network mobility based on individual nodes speeds. Recommendations for future research would include the determination of additional network management tools that CBR can implement in MANETs.

What are some key factors needed in a CBR case?

From the research, it was determined that some key factors of a MANET routing CBR case include the node density and the speed of nodes in a network. These two factors are what separate the operating capabilities of the different MANET routing approaches. A hypernode that implements a CBR approach to network management using these factors would maintain a robust network while simultaneously improving efficiency over a barrage relay method. Recommendations for future research include determining an ad hoc routing method that works best in the case of high node density / low mobility networks.

Can CBR Case information be Captured using the System's Current Network Management Platform?

The TrellisWare CheetahNet II TW-230 system, although designed and operated using the Barrage Relay / TDMA routing scheme, still provided valuable information that would be important in an intelligent routing protocol. The density of the network can be observed at any time through the network management tools that accompany the TrellisWare system. Given the number of nodes used in the NPS experiment (e.g., Figure 24) it was easy to confirm the number of nodes displayed at any given time. A more rigorous evaluation would include larger quantities of nodes operating to verify the accuracy of this feature over time.

Unfortunately, no node speed data for any node was obtained during the experiments. The node speed was a critical factor needed in the implementation of the CBR case structure developed in this thesis; without it, a hypernode would not be able to determine the best ad hoc routing method based on the case. TrellisWare Technologies, Inc. confirmed the lack of functionality and it is planned for future software versions for the TrellisWare CheetahNet II TW-230 radios. Recommendations for future research include studying the best method of characterizing network aggregate node speed for the CBR case structure presented in this thesis.

B. RECOMMENDATIONS

From the experiments, it was determined that there is a direct correlation between the SNR and link quality associated with a given link between nodes. The information could be easily obtained from the TrellisWare's network management software tools. The battery life, in percentage levels, could also be obtained from the TrellisWare's network management system. The SNR and the Battery life of the nodes is a very important finding; with those two metrics, the routing metric could be used to determine the cost of a given route, and the costs of each route could be compared to determine the most efficient route. Of the two factors deemed necessary to the structure of a CBR case (i.e., node density and aggregate node mobility) only node density could be obtained. Node mobility levels based on node speeds is definitely a recommendation for future research when the functionality is added to the TrellisWare CheetahNet II TW-230 radio system.

Other recommendations for research include a comparison of the TrellisWare CheetahNet II TW-230 radio system to other MANET solutions of interest to the Marine Corps, including the Wave Relay systems. An analysis that simulates the transmission of a message in one of the Ad-Hoc protocols versus the Barrage Relay / TDMA transmission scheme would also be beneficial to the Marine Corps in its quest for a next generation communications system. In addition, the SNRs collected were obtained by the radio system itself; an independent analysis evaluating the accuracy of SNR levels at the receiving antenna would be beneficial as well.

APPENDIX A: “COLBERT.JAVA”

The following code was produced by Professor Ted Huffmire to parse the unrefined SQLite database file containing the overhead message traffic among TrellisWare nodes during EMO LOE3. The code was produced on May 20, 2013.

```
import java.io.*;
class Colbert
{
   public static void main(String args[])
   {
            //System.err.println("" + args.length);
            String fn = args[0];
            //System.err.println(args[0]);
            BufferedReader br = null;
            try {
               br = new BufferedReader(new FileReader(fn));
            } catch (Exception e) {
               handleEx(e);
            }
            while (true) {
               String s = "";
               try { s = br.readLine(); } catch (Exception e) { handleEx(e); }
               if (s == null) break;
               int index = s.indexOf("<m_linkQuality>");
               if (index != -1) {
                        s = s.substring(index + 15);
               }
               index = s.indexOf("</m_linkQuality>");
               if (index != -1) {
                        String linkquality = s.substring(0, index);
                        s = s.substring(index);
                        System.out.print(linkquality + " ");
               }
               index = s.indexOf("<m_linkQualityColor>");
               if (index != -1) {
                        s = s.substring(index + 20);
               }
               index = s.indexOf("</m_linkQualityColor>");
               if (index != -1) {
                        String linkqualitycolor = s.substring(0, index);
                        s = s.substring(index);
                        System.out.println(linkqualitycolor);
               }
            }
            try { br.close(); } catch (Exception e) { handleEx(e); }
   }

   public static void handleEx(Exception e) {
            System.err.println("" + e);
            e.printStackTrace();
   }
}
```

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SUPPLEMENTAL: DATA COLLECTED FROM MARINE CORPS WARFIGHTING LAB EXERCISE AND NPS EXPERIMENTS

The data collected from the experiments are contained in three Microsoft Excel files. This data were analyzed for trends, resulting in the conclusions presented in Chapter V.

The first file, titled "20130518MCWLtestresults_parsed.xlsx" is the collection of data resulting from the Marine Corps Warfighting Lab's Limited Objective Experiment three. The original file is a text file and contained extraneous information. Professor Ted Huffmire from the Cyber Academic Groups, created a java program named "colbert.java" to remove the extraneous information, leaving behind the SNRs and the link color associated with the received SNR.

The second file, titled "20130522NPStestresults_parsed.xlsx" contains the data collected from the vehicle and foot patrols in a simulated urban environment aboard NPS and Monterey. The original text file that contained the data was also parsed by a program written by Professor Huffmire. The resultant Microsoft Excel file contained only the necessary information for analysis of node battery and position location information: battery percentage levels, GPS grid locations, and node speeds, although only speeds of "0.0" were collected during the entire experiment.

The third file, titled "20130524_BatteryTestResults.xlsx" contains the data collected from the third experiment in Chapter IV which entailed the charging and discharging of a battery while recording the voltage levels and battery percentage levels at regular intervals until the battery failed.

All data files are available at the Naval Postgraduate School's Dudley Knox Library for review.

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